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Landfill Bioreactor Performance

Second Interim Report
Outer Loop Recycling & Disposal Facility
Louisville, Kentucky

National Risk Management Research Laboratory
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Notice

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Foreword

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by U.S. EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director
National Risk Management Research Laboratory

Executive Summary

A bioreactor landfill is a landfill that is operated in a manner that is expected to increase the rate and extent of waste decomposition, gas generation, and settlement compared to a traditional landfill. This Second Interim Report was prepared to provide an interpretation of field data collected as part of a multi-year Cooperative Research and Development Agreement (CRADA) between the U.S. Environmental Protection Agency (U.S. EPA) and Waste Management, Inc. (WM). The CRADA was established to evaluate the performance of landfill bioreactor units at the WM Outer Loop Landfill, located in Louisville, Kentucky. This report follows the September 2003 U.S. EPA document *Landfills as Bioreactors: Research at the Outer Loop Landfill, Louisville, Kentucky, First Interim Report* (i.e., the First Interim Report, EPA/600/R-03/097), which presented a complete description of the landfill study sites and the data collection procedures.

The Outer Loop Landfill Bioreactor (OLLB) project considers solid waste decomposition, moisture balance, landfill gas generation, and leachate quality to evaluate the effect of bioreactor operations on municipal solid waste (MSW) decomposition. Three types of landfill cells were evaluated in the OLLB study: (i) a Control cell, in which no liquids were added; (ii) a cell in which liquids were added after the cell had been completely filled with waste (i.e., the Retrofit cell); and (iii) a cell in which liquids and air were added as the waste was placed in the landfill (i.e., the As-Built cell). The monitoring data were sequentially evaluated to identify trends in solid waste decomposition, moisture retention, landfill gas quality and quantity, and leachate quality. One must recognize the limitation of data presented in this report in establishing long-term trends in the operation of bioreactor landfills. Below is a brief description of data evaluation presented in this report.

<u>Operations</u>

- The results of the moisture balance calculations indicate an increase in moisture content of six to seven percent in the As-Built cells, an increase of approximately one percent in the Retrofit cells and a slight decrease in the Control cells during the study period;
- Data regarding leachate head in the sump, *which was used as an indirect indicator of leachate head on the liner*, indicated that operating a landfill as a bioreactor caused an overall increase in leachate head in the sump compared to the Control cells. However, in all cases, the average leachate level on the liner was well below the required 0.3 m (1 ft);
- To date, there is no indication that the bottom liner system of the test cells was compromised while installing liquid application features, or while applying liquid through those features;
- Although leachate breakouts occurred intermittently in the bioreactor landfill cells, no significant leachate breakout occurred that would result in any surface-water quality impacts;
- The lack of significant leachate breakouts (breakouts resulting in surface water quality impact) and the lack of landfill gas emission problems (methane surface emissions were detected, however at concentrations less than 500 ppm) suggest that, to date, the Outer Loop Bioreactor Landfill has been operated in a manner that will minimize problems related to excessive pressures in the cells;
- There were indications of "watering-out" of gas collection wells and trenches which was addressed by using submersible pumps to pump out the free standing liquid;
- During the period of the study, there was an increase in landfill gas collected from the bioreactor areas. Therefore, it is not possible to conclusively know what affects the watering-out of the collection features have on the gas collection efficiency;
- During the period of the study, there were no signs that "watering-out" of the gas collection wells posed a geotechnical instability problem at the site;
- There was no indication of clogging in the leachate collection system during the study period; and

- Overall, the bioreactor landfill cells generally met the criteria of Subtitle D of the Resource Conservation and Recovery Act for design and operation of MSW landfills. Data, from this site, suggest that other well-designed and well-operated bioreactor landfills can also be operated in compliance with the requirements of Subtitle D.

Solids Decomposition

- The solids composition data support conclusions reached by previous research that the operation of an MSW landfill as a bioreactor results in accelerated solids decomposition. All solid waste monitoring parameters showed accelerated waste decomposition in one of the As-Built bioreactor landfill cells relative to the Control cells. However, results were as not as conclusive for the second As-Built bioreactor landfill cell. The relatively young age of the solid waste made definitive decay rate estimates difficult.

Landfill Gas

- Results indicate that, although it is variable, the rate of landfill gas generation in the As-Built bioreactor landfill cells was greater than that of the Control cells, potentially providing a greater rate of energy production if collection occurred early and consistently;
- The landfill gas decay constant for As-Built bioreactor landfill cells was evaluated to be 0.16 yr^{-1}while the Retrofit cells and the Control cells had a k value of approximately 0.061 yr^{-1}; and
- Although the concentration (ppmv) of non methane organic carbon (NMOC) in the collected landfill gas did not appear to be higher in the landfill bioreactor cells compared to the Control cells, the overall production was higher because of the higher gas flow rate.

Leachate Quality

- The leachate quality test results were generally well correlated to the age of the waste for each cell for the study period. However, no strong correlations were found between leachate quality and accelerated waste decomposition in the bioreactor landfill cells, as the bottom, most degraded part of the solid waste mass has the largest impact on the leachate quality;
- Evaluation of the biochemical oxygen demand to chemical oxygen demand ratio (which is generally a strong indicator of organic solids decomposition) revealed that waste decomposition in the As-Built bioreactor landfill cells may have been accelerated compared to the Control cells; and
- Liquids that were added to the Retrofit cells were pre-treated to decrease ammonia concentrations. This was effective since leachate quality test results from this study showed a decrease in ammonia concentration during the study period in the Retrofit bioreactor landfill cells.

Overall, the analysis of the data collected during the first five years indicate that the addition of liquids increased the moisture content of waste in the landfill bioreactor cells and accelerated waste degradation. Leachate quality and solid waste decomposition data indicate that waste degradation was enhanced in the As-Built landfill bioreactor cells. Landfill gas quantity data indicate that the decay rate was highest in the As-Built cells and lowest in the Control cells as expected.

Future Activities

To substantiate the effectiveness of landfill bioreactors, research is focused in the following areas:

- Evaluate and adjust sampling frequency of the various monitoring/operational parameters;
- Examine NMOC emissions through various landfill covers;
- Evaluate alternative approaches to assess and engineer controls for fugitive emissions;
- Determine shear strength as a function of age of the wastes and assessment of landfill stability;
- Identify the effectiveness of landfill bioreactors in enhancing carbon sequestration; and
- Identify the effectiveness of bioreactors in treating/containing nanoparticles.

It is anticipated that the data collected throughout the remainder of the CRADA test period will further support the conclusions reached in this report and allow better definition of the correlations described. Finally, it is concluded that, if the trends illustrated in this report for all of the monitored media (i.e., solids, liquids, and gases) are confirmed at the end of the CRADA test period, then there will be a significant increase in our understanding of bioreactors and increased potential to predict their performance.

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List of Acronyms

ANOVA	Analysis of Variance
BMP	Biochemical Methane Potential
BOD	Biological (or Biochemical) Oxygen Demand
C&D	Construction and Demolition
CAA	Clean Air Act
CE	Collection Efficiency
CFR	Code of Federal Regulations
CH:L	Cellulose plus Hemicellulose to Lignin
COD	Chemical Oxygen Demand
CQA	Construction Quality Assurance
CRADA	Cooperative Research And Development Agreement
DOC	Dissolved Organic Carbon
FML	Flexible Membrane Liner
GEM	Gas Emissions Model
GPS	Global Positioning System
HAP	Hazardous Air Pollutant
HDPE	High Density Polyethylene
HELP	Hydrologic Evaluation of Landfill Performance
ID	Inner Diameter
LCS	Leachate Collection System
LFG	Landfill Gas
MACT	Maximum Achievable Control Technology
MSL	Mean Sea Level
MSW	Municipal Solid Waste
NCSU	North Carolina State University
NESHAP	National Emission Standards for Hazardous Air Pollutants
NMOC	Non-Methane Organic Compound
NRMRL	National Risk Management Research Laboratory
NSPS	New Source Performance Standards
OLLB	Outer Loop Landfill Bioreactor
OLRDF	Outer Loop Recycling and Disposal Facility
OP-FTIR	Open Path Fourier Transform Infrared
ORD	Office of Research and Development
ORP	Oxidation Reduction Potential
PCF	Pounds Per Cubic Foot
PSF	Pounds Per Square Foot
QAPP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
RD&D	Research, Development, and Demonstration
RPD	Relative Percent Deviation
SBR	Sequential Batch Reactor
SDR	Standard Dimension Ratio
SM	Standard Methods
SVOC	Semi-Volatile Organic Compound
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon

List of Acronyms (continued)

TVA	Total Volatile Acid
UCL	Upper Confidence Level
U.S. EPA	United States Environmental Protection Agency
VFA	Volatile Fatty Acid
VOA	Volatile Organic Acid
VOC	Volatile Organic Compound
VS	Volatile Solid
WM	Waste Management, Incorporated
XL	eXcellence and Leadership

Chapter 1. Introduction

1.1 Landfill Bioreactor Technology

In 2005, more than 230 million tons of municipal solid wastes (MSW) were generated in the United States with 57 percent of that waste managed via disposal in MSW landfills (U.S. EPA 2006a). The majority of these landfills are permitted under Subtitle D of the Resource Conservation and Recovery Act (RCRA) and are managed as "dry tombs" where explicit controls are implemented to minimize liquid introduction and infiltration into the solid waste mass. Since the 1970s, the potential benefits of moisture addition, or leachate recirculation, into MSW landfills have been examined by the U.S. EPA as well as many other researchers. These potential benefits include the rapid decomposition of degradable organics, the rapid generation of landfill gas (LFG), and the stabilization (e.g., low concentration of organics, metals, etc.) of landfill leachate. Since the 1990s, the coupled effects of controlled introduction of leachate and groundwater (and sometimes air) as well as LFG extraction have been incorporated into the concept of what is known as the "landfill bioreactor".

The concept is particularly appealing since under the current Subtitle D regulations landfill owners are financially responsible for the environmental care and management of their landfills for a minimum of 30 years after closure. If a landfill bioreactor can be demonstrated to consistently enhance/accelerate waste degradation and reduce to long term risk associated with the site to an acceptable level, then reduced post closure care may be considered for such sites. Although the technology related to landfill bioreactors has been investigated since the 1970s, full-scale implementation and the corresponding performance monitoring results have been limited. Under a Cooperative Research and Development Agreement (CRADA) between the U.S. EPA and Waste Management, Inc. (WM), long-term performance monitoring of MSW bioreactor landfill cells was initiated at the Outer Loop Landfill in Louisville, Kentucky. In addition to confirming/refuting the results of previous laboratory and pilot-scale studies, the Outer Loop Landfill Bioreactor (OLLB) study also focused on defining the obstacles and limitations to the full-scale implementation of the landfill bioreactor technology concepts at working MSW landfills.

1.2 Outer Loop Landfill Bioreactor

The study presented in this document was conducted at the Outer Loop Recycling and Disposal Facility, (OLRDF), which is located in Louisville, Jefferson County, Kentucky. The site has a total property area of approximately 316 hectares (780 acres) and is located on the north side of Outer Loop Road, immediately west of Interstate 65. The OLDRF is owned and operated by WM and has been used for waste disposal for approximately 35 years. The OLRDF comprises eight individual and separate landfill units, designated Units 1 through 8. Units 1, 2, 3, and 6 are inactive landfill units that are not currently receiving waste. Unit 4 is permitted as a construction and demolition (C&D) debris landfill that is currently active, and Unit 8 is a newly permitted active bioreactor landfill cell *(not included in this report)*. This study focuses on portions of Unit 5 and Unit 7, which are both permitted Subtitle D landfill units. During the study, Unit 5 was inactive, while Unit 7 actively received waste.

The bioreactor demonstrations at the OLLB represent large-scale research efforts at a full-scale operational landfill. The study covers approximately 20.2 hectares (50 acres) in three types of lined landfill units. The first was a Subtitle D landfill that was retrofitted with moisture addition piping to allow the recirculation of liquids (Unit 5). The second type of units in this study was a landfill that had a piping network (for liquids and air addition) installed as waste was being placed (Unit 7.4). The third unit was a Control cell that was developed and filled as a typical Subtitle D landfill without any intent of supplemental liquid addition (Unit 7.3). Each of the three units was divided into sub cells to provide a quasi-"duplicate" of each test cell for data quality purposes.

1.3 Project Objectives

The overall objectives for the OLLB project, previously presented in the First Interim Report, are as follows:

- Extensive monitoring of bioreactor landfill cells to understand the physical, chemical, and biological activities and changes over time within the landfill bioreactors, with particular emphasis given to characteristics of in-place solid waste, leachate, LFG, as well as waste settlement;
- Compare and contrast measured information with that of a conventional Subtitle D landfill to evaluate differences caused by the bioreactor landfill treatments;
- Incorporate statistical techniques to assess the effectiveness and protectiveness of the landfill bioreactor operational technique;
- Establish best practices and procedures required to operate landfill bioreactors;
- Establish the important and indicative parameters that should be monitored with respect to landfill bioreactor operations (i.e., critical and non-critical measurements); and
- Obtain sufficient research data to enable improvements that may be applied to future bioreactor landfills, both in an experimental capacity and as an alternative design and management method for MSW landfills.

1.4 Report Organization

This report provides a summary and interpretation of the monitoring results from 2001 to the second quarter of 2006 for the OLLB project. This report is a follow-up to the September 2003 U.S. EPA document *Landfills as Bioreactors: Research at the Outer Loop Landfill, Louisville, Kentucky, First Interim Report*, which presented a complete description of the landfill study sites, the distinction between the study units, and the data collection procedures. Although this document is a follow-up to the earlier report, this Second Interim Report is intended to be a stand-alone document. The document is organized as follows:

- Chapter 1. Provides a brief background related to landfill bioreactor technology and introduction to the OLLB project,
- Chapter 2. Summarizes previous findings regarding landfill bioreactor technology. The findings presented were usually obtained at laboratory-or pilot-scale level and served as the springboard for the OLLB project,
- Chapter 3. Provides a description of the various test cells at the OLLB site and explains the rationale for selecting the specific cells for study,
- Chapter 4. Focuses on solids decomposition and moisture balance calculations,
- Chapter 5. Focuses on landfill gas generation as well as non-methane organic carbon emissions,
- Chapter 6. Focuses on leachate quality and how they relate to waste decomposition,
- Chapter 7. Provides an evaluation of several performance criteria at the site as well as a discussion of results compared to regulatory thresholds for MSW landfills,
- Chapter 8. Presents conclusions from the study, as well as recommendations regarding ongoing and future monitoring activities at the site,
- Chapter 9. Provides a list of the cited references from the report,
- Appendix A. Provides the data validation report generated by Neptune and Company, Inc.,
- Appendix B. Provides supplemental figures related to MSW solids analysis,
- Appendix C. Presents statistical analyses of measured waste moisture content,
- Appendix D. Presents statistical analyses of measured versus calculated waste moisture content,
- Appendix E. Presents summary statistics for the hazardous air pollutant (HAP) analysis; and
- Appendix F. Presents a statistical analysis of the leachate monitoring results.

Chapter 2. Overview of Bioreactor Landfills

This chapter presents a brief overview of previous research and studies related to the bioreactor landfill concept. Many of the topics covered in this section were presented and evaluated as part of an earlier U.S. EPA document titled "*Monitoring Parameters for Landfill Bioreactors*" (U.S. EPA 2004). That document outlines monitoring at MSW bioreactor landfills based on the OLLB experience. The main purpose of that document was to provide a regulatory and research-based rationale for the various parameters that were monitored during the project. The main reason for reintroducing those parameters is to provide a basis for the re-evaluation of the effectiveness of these parameters that are presented in later chapters.

2.1 Introduction to Landfill Bioreactors

More than 230 million tons of MSW is generated in the United States annually with 57 percent of that waste disposed of in MSW landfills (U.S. EPA 2006a). Most of the MSW landfills currently in service are permitted under Subtitle D of the RCRA or Subtitle D regulations (U.S. EPA 2006a). The main purpose of MSW landfill regulations (just like other environmental regulations), is to minimize risk to human health and the environment. In the case of MSW landfills, this was accomplished by reducing possible contamination from the migration of leachate and LFG from landfill sites. Thus, Subtitle D landfill regulations outline a system that minimizes liquid infiltration into the solid waste mass by controlling the amount of moisture allowed into these landfills. Because the Subtitle D "dry tomb" landfill design incorporates features to minimize the potential for the introduction of liquids into the waste, the resulting waste mass is often maintained at relatively low moisture content. As a result, the conventional Subtitle D "dry tomb" landfill design does not promote the solid waste decomposition process. Therefore, the risk associated with environmental emissions from dry tomb MSW landfills may exist longer, justifying the need for long-term monitoring at MSW landfill sites. Current regulations require leachate and LFG emissions to be monitored for at least 30 years after closure of a landfill site or as long as environmental risk are present. Numerous small-scale and large-scale projects have demonstrated that the rate of solid waste decomposition at MSW landfills can be improved by increasing the moisture content of the waste, thereby potentially reducing the duration of the required post-closure care requirements. Increasing the moisture content of MSW by may provide the necessary liquids to accelerate waste decomposition. In addition, leachate recirculation is an economical means for leachate management at landfill sites (Pohland 1975).

Initially, most of the research examining the effects of moisture addition on solid waste degradation concentrated on leachate recirculation as a means of economically managing MSW landfill leachate. In a conventional dry tomb landfill, landfill leachate is mainly generated by rain water percolation through the solid waste. As a result, the volume of the leachate generated depends largely upon the climate, the type of waste present in the landfill, the landfill morphology, the landfill surface conditions, and the types of operations at the facility (Reinhart and Townsend 1998). Research has demonstrated that enhanced degradation of MSW is possible use leachate recirculation (Pohland et al. 1993; Townsend et al. 1996; Reinhart and Townsend 1998). Enhanced degradation in a landfill where liquids are recirculated compared to a conventional landfill, is also characterized by enhanced LFG production. When operated in a fashion that includes controlled introduction of liquids, the landfill appears to operate like a "biological reactor" or "bioreactor", as the recirculated liquids increase the moisture content of the waste and enhance the distribution of nutrients and bacteria, buffer the pH, and dilute inhibitory compounds (Reinhart and Townsend 1998; Kim and Pohland 2003). Recirculation of leachate also reduces the need and cost associated with the collection and subsequent removal of leachate from the landfill to some other on-site or off-site location for treatment through conventional biological and/or physical-chemical processes.

Research has also shown that liquids recirculated in landfill bioreactors tend to act as a medium for nutrients, provide microbial transport, and enhance the establishment of anaerobes. As a result of the increase in moisture content, a more rapid rate of solid waste decomposition is achieved when compared to conventional MSW landfills. The enhanced rate of decomposition, facilitated by the increase in moisture content, often leads to an increase in the LFG generation rate with a corresponding reduction in biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total volatile acids (TVA), and metals content in the leachate (Pohland et al. 1993; Reinhart and Townsend 1998; Sponza and Agdag 2004). The enhanced rate of landfill decomposition typically results in an increase in the rate of landfill settlement (El-Fadel 1998; Hossain et al. 2003), which may provide additional airspace. As a result, the total amount of solid waste placed in landfill bioreactors may be more than the amount placed in a dry tomb landfill of similar size. Enhancing the rate of LFG production may also improve the economics associated with gas-to-energy facilities at landfill bioreactor sites (Barlaz et al. 1990; Mehta et al. 2002). As a result of these combined effects, landfill bioreactors may reduce the long-term environmental impacts associated with the disposal of MSW in landfills.

2.2 Regulatory Overview

Solid waste regulations were established fairly recently relative to other environmental regulations. Most MSW landfills in the U.S. operate under regulations identified in Subtitle D of RCRA. The specific regulatory criteria for MSW landfills are presented in 40 CFR Part 258, which was promulgated in 1991. The main goal of these regulations is to ensure protection of human health and the environment through the establishment of minimum national criteria for MSW landfills. Subtitle D regulation specifies performance standards for the location, design, groundwater monitoring, and corrective actions for MSW landfills. In the preamble to the Subtitle D regulations, the U.S. EPA recognized that landfills are, in effect, biological systems that require moisture for decomposition to occur. The U.S. EPA further acknowledged that the increase in moisture content of solid waste landfills may provide specific benefits, which may include increasing the rate of waste stabilization, improving leachate quality, and increasing LFG production for potential energy recovery. At the time Subtitle D regulations were promulgated, however, the U.S. EPA believed that many landfills, particularly those in humid areas, already had sufficient liquid for decomposition. Therefore, the conventional opinion was that the intentional addition of liquids was unnecessary. Furthermore, it was hypothesized that intentional liquid introduction may result in operational problems, including: (i) an increase in leachate production; (ii) clogging of the leachate collection system; (iii) buildup of hydraulic head within the landfill; (iv) an increase in LFG emissions and odor problems; and (v) an increase in the potential for the leachate to be released as a pollutant due to leachate breakouts and/or run-off. These operational problems, should they occur, would likely result in adverse impacts on human health and the environment (Ikem et al. 2002).

Subtitle D regulations included provisions to prohibit the addition of liquids to MSW landfills. Specifically 40 CFR 258.27 states “bulk or non-containerized bulk liquid waste may not be placed in MSW landfill units.” Subtitle D regulations, however, allow for recirculation of leachate and gas condensate generated from the gas recovery process as long as the landfill design includes certain liner requirements. Because of the lack of data on the performance of landfill bottom liners, the U.S. EPA initially required (at a minimum) that MSW landfills that recirculate leachate and gas condensate use single composite liners to contain leachate and prevent it from contaminating the underlying soil and groundwater. MSW landfill liner systems typically consist of high density polyethylene (HDPE) geomembranes, geosynthetic clay materials, or compacted clay (Foose et al. 2002). In addition to requiring composite liners, the regulations require that a demonstration be provided to assure that the added volume of liquid will not increase the liquid (i.e., hydraulic) head on the liner to more than the allowable 30 cm (1 ft). Because of the self-implementing nature of the regulations, the permitting of leachate recirculation systems for MSW landfills was delegated to the approved state regulatory agency or tribal community. Thus, regulations regarding MSW landfills tend to vary between states, which allow various degrees of flexibility within the law.

The U.S. EPA provided limited regulatory flexibility to allow landfill bioreactors because of promising results from research regarding landfill bioreactors. Most notable was the introduction by U.S. EPA in 1995 of Project XL (eXcellence and Leadership). For the case of MSW landfills, Project XL allowed for leachate, as well as other industrial liquids, to be added to Subtitle D landfills that do not meet the composite liner criterion. In turn, the designers of the Project XL landfill bioreactors hoped that the leachate recirculation/LFG recovery requirements would enhance groundwater protection and provide for additional capacity to accommodate more waste at individual landfills, thus extending the life of existing landfill cells. Unfortunately, because of difficulty in obtaining a Project XL landfill bioreactor permit, only five landfills were permitted under this effort nationwide before the U.S. EPA ceased accepting Project XL proposals in 2003.

In 2003, the U.S. EPA defined landfill bioreactors as MSW landfills that utilize liquids other than leachate and gas condensate to achieve an average moisture content of more than 40 percent on a wet weight basis. In its final rule on National Emissions Standards for Hazardous Air Pollutants (NESHAP) for landfills and the Maximum Achievable Control Technology (MACT) regulations, the U.S. EPA required landfill bioreactors with a total disposal capacity equal to or greater than 2.5×10^6 Mg (or m^3) to include a system to actively collect and control LFG that will commence operation within 180 days after liquids addition or after the average landfill moisture content reaches 40 percent, whichever occurs later (FR 2003).

Realizing the potential benefits of adding moisture to reduce the long-term risk associated with MSW landfills, the U.S. EPA promulgated the Research, Development, and Demonstration Permits for Municipal Solid Waste Landfills (RD&D rule) in 2004 (FR 2004). Under this rule, the U.S. EPA allowed approved states to permit landfill bioreactors under Subtitle D regulations. The RD&D rule deviates from the Subtitle D regulations in that it allows approved states to waive some provisions of the Subtitle D landfill operating criteria (excluding hazardous waste prohibition and explosive gas control), design criteria, and final cover criteria. RD&D permits, as well as the rule itself, are temporary modifications to the original Subtitle D regulations. The RD&D permit for a given MSW landfill is initially approved for three years, with optional three year renewals for a maximum of 12 years. Landfill bioreactors permitted under the RD&D rule are required to submit annual reports that summarize data obtained during each year and assess progress towards ultimate solids stabilization.

Approved states may issue landfill permits under the RD&D rule to allow the addition of non-hazardous industrial liquids to MSW landfills that use conventional composite liners or alternative liner systems. The landfill owner must also demonstrate to the appropriate State Director that the MSW landfill that is designed and operated as a landfill bioreactor under the RD&D rule does not pose an additional risk to human health or the environment beyond what can result from its operation as a dry tomb Subtitle D MSW landfill. Just like the Subtitle D regulations, the RD&D rule is self-implementing, giving each state or tribal community the authority to permit landfill bioreactors that may otherwise not have been allowed previously under Subtitle D regulations.

There are insufficient data on the behavior of landfills that use industrial liquids as a source of moisture. Since the RD&D rule is temporary (i.e., 12 years), the U.S. EPA Office of Research and Development (ORD) is actively gathering data that may help in supporting many of the concepts envisioned by this rule. The data gathered by ORD will not only concentrate on the performance of the containment system (e.g., leachate and LFG collection, liners, slope stability, etc.) but also on the microbial stabilization within the landfill unit. Data are currently being collected from four Project XL landfills and the two MSW landfills that have CRADAs with the U.S. EPA. More information regarding the other Project XL landfills can be found on the webpage http://www.epa.gov/projectxl.

2.3 Anaerobic Decomposition Fundamentals

Waste in an MSW landfill does not have a single age because waste is placed incrementally in the various cells throughout the life of the facility. Rather, waste of different ages is associated with the various cells within the landfill and their respective “stabilization” stage or phase (Pohland et al. 1993). As can be seen in Figure 2-1, the different MSW landfill stabilization phases often overlap and can be viewed collectively, which tends to limit the industry’s understanding of the various phases and their interaction. As shown in Figure 2-1, the initial phase results in aerobic decomposition followed by four stages of anaerobic decomposition. Thus, the majority of MSW landfill decomposition occurs under anaerobic conditions. It is noted that virtually all MSW landfills undergo these five stages of stabilization and that operating an MSW landfill as a landfill bioreactor has an effect only on the rate and not the sequence (and potentially the duration) of the stabilization phases (Pohland and Al-Yousfi 1994; Reinhart and Townsend 1998; Kim and Pohland 2003). Thus, it is important to understand each of the

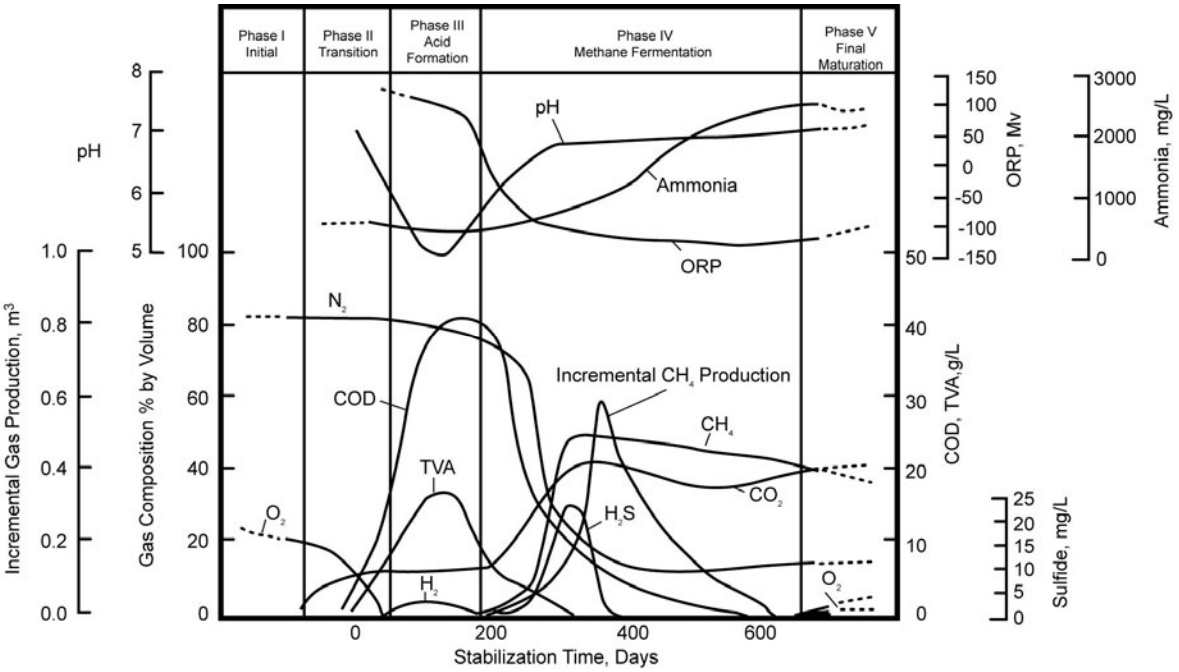


Figure 2-1 Phases of Solid Waste Decomposition (source: Pohland et al. 1993)

stabilization phases individually. After a short-duration aerobic phase, it is generally recognized that there are four more steps involved in the anaerobic solid waste degradation and stabilization process, with each step involving a set of separate and distinct microbial populations. These steps/phases are shown in Figure 2-1 and further described below. Successful conversion and stabilization of the waste is dependent on microorganisms performing their respective functions in syntrophic relationships. The application of these phases to an MSW landfill setting is briefly discussed below (Pohland 1975; Pohland et al. 1993).

2.3.1 Phase I (Initial Adjustment)

This phase is sometimes referred to as the lag phase. As the waste is placed in the landfill, the void spaces contain oxygen (O_2). With compaction, the O_2 content of the landfilled solid waste gradually decreases. As moisture becomes available and the microbial population density increases, biochemical decomposition under aerobic conditions is initiated.

2.3.2 Phase II (Transition)

The transition phase is relatively short-lived as the O_2 is rapidly consumed by the bacteria present, resulting in a transition from aerobic to anaerobic conditions. During this phase, the primary electron acceptors become nitrates and sulfates, rather than O_2, with the displacement of O_2 by carbon dioxide (CO_2) in the effluent gas.

2.3.3 Phase III (Acid Formation)

This phase is marked by the onset of the hydrolysis of the biodegradable fraction of the solid waste, leading to a rapid increase in the concentration of volatile fatty acids (VFAs) in the leachate. This also corresponds to a decrease in pH from approximately 7.5 to 5.6 (Pohland et al. 1993). During this phase, the decomposition intermediates such as VFAs contribute to a high COD and the long-chain volatile organic acids (VOAs) are converted to acetic acid ($C_2H_4O_2$), CO_2, and hydrogen (H_2).

The presence of high levels of VFAs in the leachate will increase both BOD and VOAs, leading to the onset of H_2 production by fermentative bacteria and H_2-oxidizing bacteria. The H_2 generation phase is comparatively short-lived as it terminates by the end of this phase. This phase is also marked by an increase in the biomass of acidogenic bacteria as well as a rapid consumption of substrates and nutrients.

The drop in pH may cause concomitant mobilization and the possible complexation of metal species that are more soluble at a low pH.

2.3.4 Phase IV (Methane Fermentation)

Intermediary products appearing during the acid formation phase (i.e., mainly acetic, propionic, and butyric acids) are converted to methane (CH_4) and CO_2 by methanogens. As a result of the consumption of VFAs by methanogens, the pH moves back to neutrality. The organic strength of the leachate (as characterized by high BOD) is dramatically decreased in correspondence with increases in gas (i.e., CH_4 and CO_2) production. This phase also signifies the longest overall time duration and represents the period when the majority of the waste decomposes.

2.3.5 Phase V (Final Maturation and Stabilization)

The final stage of solid waste decomposition is characterized by a lower rate of biological activity due to the limiting nutrients such as phosphorus. During this stage, landfill CH_4 production is almost negligible. O_2 and oxidized species may slowly reappear as O_2 permeates from the atmosphere with a corresponding increase in oxidation-reduction potential (ORP) in the leachate. It is hypothesized that residual organic materials may slowly be converted to gas in this phase, with the possible production of humic-like substances. To date, the U.S. EPA has no documentation of an MSW landfill exhibiting such characteristics.

2.4 Key Monitoring Parameters for MSW Landfill Bioreactors

The landfill bioreactor RD&D rule allows for the controlled introduction of liquids into Subtitle D MSW landfills to accelerate the decomposition of biodegradable organics. To understand the decomposition process, it is important to understand the type and role of microorganisms that contribute to this process. The anaerobic waste degradation process requires at least four different groups of microorganisms (Parkin and Owen 1986; Pohland et al. 1993). These microorganisms occur naturally in MSW but require different conditions to achieve optimal performance. The kinetics of microorganisms in landfill bioreactors have not been widely investigated, likely because these groups of microorganisms (and other anaerobes in general) are harder to culture compared to aerobes. In fact, it is now recognized that the majority of the microorganisms in environmental systems cannot be easily cultured (Amman et al. 1995; Hugenholtz et al. 1998; Jjemba 2004). As a result, there is a need to use molecular-based non-culture techniques to study the microbial populations in MSW landfills as solids decomposition progresses. Therefore, instead of directly studying the “cause” or source of the decomposition, researchers are often forced to indirectly study waste stabilization by monitoring the “effect” of the decomposition process. As a demonstration of this, Lay, et al. (1998), examined the abundance and activity of methanogens in simulated landfill columns. In that study, both the cumulative CH_4 production and moisture content were higher in the columns that included recirculated leachate. Recirculation of leachate also shortened the initial lag phase. The specific microbes responsible for these mechanisms (i.e., the cause) were not thoroughly investigated, but the results of the microbial activity (i.e., the effect) were demonstrative.

In addition to the biological parameters that can be monitored, there are some physical and chemical parameters that can be monitored that collectively confirm the optimal operation of landfill bioreactors. The remainder of this section presents results from previous studies that focus on these parameters. It should be noted that the optimal ranges presented in this review may not apply to all landfills as the composition of waste varies greatly. Therefore, in response to the heterogeneous nature of MSW, waste stream variability, and differences in environmental and climate conditions, the use of “Control cells” (i.e., conventional dry tomb cells) at operating landfill bioreactor facilities is encouraged to help understand the site-specific performance of landfill bioreactors compared to the conventional landfill units. Unfortunately, the literature does not include numerous example projects where Control cells were systematically constructed and operated; while Control cells were integral to the study at the OLRDF. For research purposes, it is recommended that landfill cells used as a control be comparable to the landfill bioreactor cells in age, depth, and composition of waste so that specific differences in monitoring parameters may be evaluated more effectively. They should be monitored separately whenever possible to demonstrate specific impacts of landfill bioreactor operations on the volume and quality of leachate, the volume and composition of LFG generated, changes in the waste mass, and effects on the leachate collection system. While it is believed that the use of Control cells associated with landfill bioreactor are beneficial and that use of the Control cells will likely help in the assessment of site-specific data, it is understood that the use of Control cells may not be feasible in all cases.

2.4.1 Physical Monitoring Parameters

2.4.1.1 Geotechnical Considerations

Slope stability is an important parameter in MSW landfill design, particularly with regard to landfill bioreactors. Often landfill slope stability focuses on the stability of the final landfill configuration. Operating landfills as bioreactors increases the importance of a slope stability assessment as part of the overall design, not only for the final configuration but also for when the landfill is at interim grades. Large changes in liquid levels in the landfill impact the development of pore pressures, which can influence slope stability. Pore pressures may increase in landfill bioreactors because of the addition of liquids and the concurrent increase in the rate of LFG production. However, there are little well documented field data available to substantiate this possibility.

Several approaches for predicting and periodically assessing stability in landfills have been proposed (Bachus et al. 2004). Stability calculations can be conducted using the strength properties of the waste and foundation soils, the geometry of the waste mass, and the pore pressures within the waste and foundation soils. Unit weight, shear strength and frictional characteristics of MSW vary widely because of differences in waste characteristics and compaction techniques. The unit weight of MSW was reported by Landva and Clark (1990) to range from 320 to 1580 kg/m^3 (20 to 99 pcf). As expected, the shear strength of the waste and the calculated stability of the landfill depend on the composition of the waste. MSW may have an internal friction angle of 1 degree with cohesion as large as 2200 psf to a friction angle as high as 36 degrees with no cohesion (Singh and Murphy 1990). Kavazanjian et al. (1995) reviewed the technical literature and recommended design shear strength for waste that is represented as a bilinear Mohr-Coulomb failure envelope exhibiting a friction angle of 33 degrees with minimum shear strength of 550 psf. Large-scale laboratory direct shear tests conducted on “conventional” and bioreactor landfill wastes indicate similar strength parameters. Leachate levels in the waste and liquid in the subsurface also affect slope stability.

In conjunction with a slope stability study, it is recommended that operators follow simple guidelines to promote landfill bioreactor slope integrity. Operators should avoid any excavation at the toe of the slope that can create local zones of high stress that may potentially lead to instability. Operators should also avoid filling waste in cells at steep grades [i.e., greater than 3 horizontal to 1 vertical (3H:1V)]. The placement of fill for on-site roads and a component of the cover may also lead to a translational or veneer instability, and should be considered during design (Stark et al. 2000).

As required under Subtitle D regulations, leachate head on a landfill bottom liner should not exceed 30 cm (1 ft). The addition of moisture into the landfill may cause excess amounts of leachate to build up on the bottom liner if the liquids are not effectively removed. Before the addition of moisture into a landfill bioreactor, therefore, the ability of the leachate collection system (LCS) to effectively minimize the potential impacts of increased leachate flow must be explicitly considered. Performance of the LCS and resistance to clogging should also be examined during design and monitored during operation. Potential clogging of the LCS may lead to a buildup of leachate within the drainage layer, causing the head on the liner to exceed 30 cm (1 ft). As described previously, this may increase the potential for slope instability. Alkalinity, hardness, iron, and manganese compounds, total organic carbon, COD, and BOD are all involved in reactions that can result in buildup of precipitates that could potentially lead to LCS clogging (Fleming et al. 1999; Rowe et al. 2000; Cook et al. 2001; Rittmann et al. 2003). Monitoring the concentration of these parameters may provide an indication as to whether leachate concentrations approach saturation levels for calcium carbonate and other compounds that contribute to clogging and poor LCS efficiency. LCS clogging may also be caused by the settling of suspended particles from the leachate and biological growth on or in the LCS (Koerner and Koerner 1995).

2.4.1.2 Mass Balance

It is important that the mass of the landfilled solid waste within each landfill bioreactor cell be identified and recorded. Conducting regular surveys of in-place volume and total disposed mass can be helpful in estimating the density of solid waste placed and may provide insight into waste decomposition. As the solid waste decomposes, the density of the landfill tends to increase (Tiquia et al. 2002). Parameters that may assist with mass loading calculations are presented in Table 2-1. With regard to the total disposed mass, it is recognized that soil used as daily cover needs to be considered in any mass calculation. It has been recommended to avoid daily cover materials with a low permeability to minimize perched leachate zones within the landfill (U.S. EPA 2002). Efforts may be made during site operations to remove temporary cover, temporary roadways, and piles of soils used for daily cover prior to the placement of waste in a particular part of the cell. Additionally, using materials other than soil (e.g., temporary tarps, foams, etc.) as daily cover may be an effective alternative in preventing perched leachate zones.

Table 2-1 Mass Balance Monitoring Parameters and Frequencies

Parameter	Frequency	Units
Visual Landfill Inspection	Daily	-
Mass of Landfilled MSW	Daily	Mg (tons)
Mass of Landfilled Construction and Demolition Waste	Daily	Mg (tons)
Mass of Soil (other than daily cover)	Daily	Mg (tons)
Type of Daily Cover	Daily	
Mass or Volume of Daily Cover	Daily	Mg (tons) or m^3 (yd^3)
Landfill volume	Quarterly	m^3 (yd^3)
Settlement	Quarterly	m (ft)

2.4.1.3 Moisture Balance

A key component in operating a landfill as a bioreactor is the introduction of moisture from internal (i.e., leachate) and external (e.g., precipitation, stormwater, groundwater, and industrial liquid waste streams) sources into the landfill. In general, the decomposition and select stabilization rate of biodegradable solid wastes increases with increasing moisture content of the waste (El-Fadel 1998; Olayinka 2003). Research has shown that the optimum moisture content for biological degradation is greater than 40 percent (Pohland et al. 1993; Reinhart and Townsend 1998). Deliberate moisture addition to the landfill should be applied uniformly to the extent practicable to evenly wet the waste and to reduce differential settlement. Typical moisture addition techniques include applying liquids to the surface and to the subsurface. Surface applications include spray irrigation and surface ponds. Subsurface techniques include horizontal trenches and vertical wells, in addition to other methods such as permeable blankets, which have been described elsewhere (Haydar and Khire 2006). Limited research has been performed at full-scale landfills regarding design guidelines for subsurface application techniques; however, hydraulic properties of waste were estimated using leachate recirculation via vertical wells (Jain et al. 2006). Similarly, hydraulic properties while using horizontal injection have been reported (Townsend and Miller 1998, Haydar and Khire 2005). As described previously, an increase in landfill moisture content that results in a build-up of pore pressure may decrease slope stability. Assuming the volume of water consumed to be negligible during waste hydrolysis, moisture balance can be calculated as presented in the following equation:

$$\Delta S = \text{Moisture}_{in} - \text{Leachate}_{out} \qquad \text{Equation 2-1}$$

Where:

ΔS = net moisture storage;
Leachate_{out} = leachate generated by the landfill; and
Moisture_{in} = liquids added into the landfill, including precipitation.

As mentioned previously, liquids addition occurs in various forms including, but not limited to, the introduction of leachate, stormwater, liquid waste, and municipal and industrial wastewater. Parameters that assist in performing a water balance are presented in Table 2-2. These should be monitored daily when liquids are being introduced into the waste. It is also important to take into account the moisture content of the incoming waste when using the moisture content of the waste to quantify or to assess moisture balance.

Table 2-2 Liquid Addition Monitoring Parameters

Parameter	Frequency	Units
Volume of Leachate Added	Daily	L (gal)
Rainfall	Daily	mm (inch)
Volume Outside Liquid Added (e.g., Groundwater, Industrial Wastewater)	Daily	L (gal)
Volume of Leachate Generated	Daily	L (gal) of leachate generated by the landfill bioreactor cells only
Mass of Sludge Addition	Daily	Mg (tons)
Wet Basis Moisture Content of Sludge Added	Daily	Percent (M/M)

2.4.2 Analytical Monitoring Parameters

2.4.2.1 Leachate Monitoring

Leachate monitoring parameters presented in this section may be used to enhance the operational control of MSW landfill bioreactors. These parameters are categorized as either “Tier 1” or “Tier 2”, shown in Tables 2-3 and 2-4, respectively. Tier 1 parameters are relatively inexpensive to obtain. Tier 2 parameters are usually more time intensive to assess and, as a result, the testing is incrementally more expensive than testing for Tier 1 parameters. The extent and frequency of leachate monitoring at each site will ultimately be dependent on local, state, and federal regulations. It is, however, recognized that the value of some of the individual parameters can change significantly over the life of the landfill bioreactor cell. It is noted that the constituents listed in Table 2-3 and 2-4 are simply suggested monitoring parameters, and the specific leachate monitoring needs and requirements of a bioreactor landfill should be evaluated on a site-specific basis. Because of their importance in understanding the decomposition process and therefore attaining a properly functioning landfill bioreactor, some of these monitoring parameters are discussed in detail below.

2.4.2.1.1 Leachate Temperature

Research suggests that anaerobic processes are optimized when the waste is within either the mesophilic (30 to 38 °C (86 to 100 °F)) or thermophilic (50 to 60 °C (122 to 140 °F)) temperature range (Parkin and Owen 1986). The higher thermophilic temperatures enhance the rate at which organic matter is converted to VOAs but lead to a lower yield of CH_4 compared to the lower mesophilic temperatures (Pohland et al. 1993). This trend is possibly attributed to an increase in the activity of acetogens and a decrease in the activity of methanogens. Optimum CH_4 generation from solid wastes, however, was found to occur at 41°C (105.8 °F) (Hartz et al. 1982). It is recognized that operating temperatures in the landfill at the thermophillic range may present concerns regarding fire, health and safety issues, and sustained vitality of the microorganisms. The maintenance of a uniform leachate temperature is believed to be a fundamental monitoring parameter that is indicative of an efficient anaerobic stabilization process.

Since landfill temperature is not typically controlled by the operator, the temperature ranges stated above reflect a combination of effects due to ambient temperature conditions, microbial activity, and the extent and effectiveness of insulation provided by the specific landfill configuration. In a study conducted at the Outer Loop Landfill in Louisville, Kentucky, the temperatures of the leachate were initially approximately 7° C (45 °F) but steadily increased to 30 °C (86 °F) or higher within a few months after operating the landfill as a bioreactor (U.S. EPA 2003). While an increase in leachate temperature may be reflective of waste degradation in a landfill, it is not solely indicative of biological activity. Leachate temperature may also be affected by ambient temperature as well, depending on the leachate sampling location.

Table 2-3 Tier 1 Landfill Bioreactor Leachate Monitoring Parameters and Frequency

Parameter	Method	Frequency
Static head on Liner	Pressure Transducer	(1)
Temperature	Thermometer	Monthly
pH	U.S. EPA(2) 9045C	Monthly
Conductance (µSm/cm)	Field Electrode	Monthly
Total Dissolved Solids (mg/L)	SM(3) 160.1 (C)	Monthly
Alkalinity (mg/L as $CaCO_3$)	SM(3) 310.1	Monthly
Anions (mg/L)	SM(3) 300.1	Monthly
Cations (mg/L)		Monthly
Chemical Oxygen Demand (mg/L)	SM(3) 410.4	Monthly
Biochemical Oxygen Demand (mg/L)	SM(3) 405.1	Monthly
Total Organic Carbon (mg/L)	EPA(2) 9060	Monthly
Total Phosphorous (mg/L)	SM(3) 365.2 (C)	Monthly
Ortho Phosphate (mg/L)	SM(3) 365.2 (C)	Monthly
Ammonia (mg/L)	SM(3) 350.1 (C)	Monthly
Nitrite (mg/L)	SM(3) 300.1	Monthly
Nitrate (mg/L)	SM(3) 300.1	Monthly

Notes:
1. Head on the liner should be monitored continuously, however, it is suggested that a weekly average is reported.
2. U.S. EPA SW-846 Test Methods for Evaluating Solid Wastes.
3. U.S. EPA Methods for Chemical Analysis of Water and Wastes.

Table 2-4 Tier 2 Landfill Bioreactor Leachate Monitoring Parameters and Frequency

Parameter	Method	Frequency
Volatile Organic Compounds(1) (VOCs) (µg/L)	SW-846 8260 (B)	Quarterly
Semi-Volatile Organic Compounds (SVOCs) (µg/L)	SW-846 8270 (B)	Quarterly
Volatile Fatty Acids (mg/L)	GC MS	Quarterly
Arsenic (mg/L)	SW-846 6010(prepared per SW-846 3005)	Quarterly
Barium (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Cadmium (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Calcium (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Copper (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Chromium (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Iron (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Lead (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Magnesium (mg/L)	SW-846 7470 (prepared per SW-846 3005)	Quarterly
Mercury (µg/L)	SW-846 7470 (prepared per SW-846 3005)	Quarterly
Potassium (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Sodium	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Selenium (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Silver (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly
Zinc (mg/L)	SW-846 6010 (prepared per SW-846 3005)	Quarterly

Note: 1. Constituents listed in 40 CFR 258 Appendix I.

2.4.2.1.2 Leachate pH

The optimum pH for anaerobic systems ranges between 6.8 and 7.4 (Parkin and Owen 1986). Initially, the leachate pH may be neutral; but after the onset of anaerobic conditions there is generally a noticeable drop in the pH especially during the acid forming phase, as discussed previously. The drop in pH is caused by the accumulation of VFAs in the leachate. However, the pH will eventually increase to neutral conditions as methanogens consume these acids. Studies conducted to compare leachate pH in conventional dry tomb MSW landfills and landfill bioreactors have shown that there may not be a significant difference in pH between the two systems. As described previously, the pH is expected to vary with time in all landfills, depending on the initial waste composition and the phase of waste degradation in the areas where the leachate passes before it is collected in the LCS.

2.4.2.1.3 Volatile Fatty Acids and Volatile Organic Acids

VFAs and VOAs affect microorganisms and the degradation processes in two primary ways. First, they have a low ionization constant (i.e., low pKa) and can readily dissociate, releasing H^+ ions that cause the pH of the system to decrease and therefore become destabilized. Second, when the acids are non-dissociated (as is typical at low pH levels), the acids are able to penetrate microbial cell membranes, establishing a pH gradient by actively transporting protons out of the cell and reducing the internal cell pH (Zoetemeyer et al. 1982; Aguilar et al. 1995). The decrease in intracellular pH in turn leads to an increased energy demand by the cell to restore pH levels leaving less energy for growth (Yamaguchi et al. 1989; Gonzalez et al. 2005). These processes lead to reduction in the rate of solid waste degradation. VOA concentrations that are in excess of 6,000 mg/L can inhibit microbial processes (Pohland et al. 1993). However, most research regarding solid waste degradation has not focused on VOAs, but rather has investigated the effect of VFAs on the menthanogenic population within the landfill.

Acidic leachate typically correlates with a high VFA content and a low CH_4 production for prolonged periods. Most common among these VFAs are acetic acid, propionic acid, and butyric acid (Barlaz et al. 1989; Kim and Pohland 2003). The amount of leachate that is recirculated affects the quantity of VFAs. If VFAs are high, methanogenesis can be inhibited by the low pH that is induced. Therefore, the volume of recirculated leachate has to be properly adjusted to minimize a buildup of VFAs. Lab-scale study results presented in Figure 2-2 demonstrate this. Figure 2-2 shows the effects of leachate recirculation on VFA accumulation in comparison to VFA generation under conventional landfill management. The leachate in "Reactor 9" was recirculated at 9 L/day (2.4 gpd) which was 13 percent of the reactor volume, whereas leachate in "Reactor 21" was recirculated at 21 L/day (5.5 gpd, 30 percent of the reactor volume). It is interesting to note that VFA buildup in the reactor with a higher leachate recirculation rate of 21 L/day (5.5 gal/day) was nearly as high as the VFAs generated in the single-pass (i.e., conventional) reactor. Furthermore, at 21 L/day (5.5 gpd), the bioreactor had a spike of almost 30,000 mg VFA/L within 30 days which can be detrimental to methanogens. This is apparent when comparing the CH_4 production in Reactor 21 to Reactor 9 (Figure 2-2). A further demonstration of the affect on degradation is that waste settlement was greater in Reactor 9 than Reactor 21 (Sponza and Ağdağ 2004). Settlement may be related to CH_4 production in anaerobic landfill systems as it is an indication of mass loss and waste degradation. At high leachate volumes, saturation, washout of the methanogens and/or ponding may occur in the reactor, thus contributing to the noted detrimental effects of the acidic condition. At this time, models that adequately predict the correct amount of leachate to recirculate have not been developed and determinations of what recirculation volume is adequate (or optimal) are generally made on a case-by-case assessment of performance.

2.4.2.1.4 Leachate Biochemical and Chemical Oxygen Demand

BOD consists of biologically degradable dissolved organics in the leachate. COD is a measure of chemically oxidizable components in leachate and reflects the amount of O_2 that is required by the bacteria to metabolize the existing organic substrate as well as the O_2 required by other oxidizable chemical compounds. One of the main consequences of operating a landfill bioreactor is the rapid reduction of BOD in the leachate. BOD values reported in the literature for conventional landfills ranged between 20 and 152,000 mg/L (Krung and Ham 1991; Chu et al. 1994; Kjeldsen et al. 2002; U.S. EPA 2003), whereas COD values range between 500 and 60,000 mg/L (Pohland et al. 1993; Reinhart and Townsend 1998; U.S. EPA 2003). By comparison, BOD values for landfill bioreactors were found to range between 20 and 28,000 mg/L (Pohland et al. 1993; Reinhart and Townsend 1998; U.S. EPA 2003).

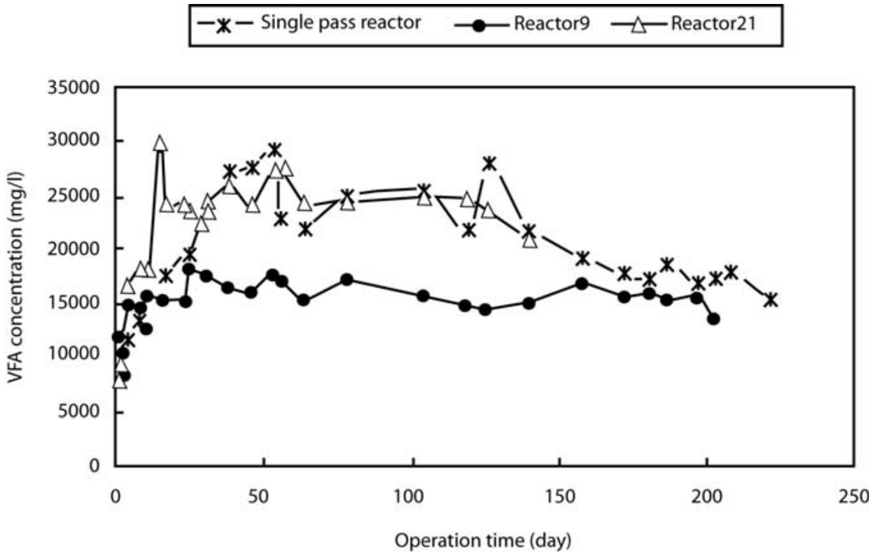


Figure 2-2 Changes in VFA in a Single Pass (Conventional) Reactor versus Bioreactor9 and Bioreactor21 over Time (Source: Sponza and Ağdağ, 2004)

While the values of BOD and COD may change individually as a function of decomposition, the ratio of BOD to COD may be used to assess the relative biodegradability of the leachate substrate. Variations in BOD and COD may be closely related to the variations observed with VFA production. As a result, the BOD/COD ratio may act as an indicator of the biodegradability of organics present in MSW. At the time of initial waste placement within the landfill, the BOD and COD concentrations were relatively low.

The initial low BOD and COD concentration is thought to be caused by the initial aerobic stabilization of the MSW or by a delay in the hydrolysis of the waste. During the acid formation phase, the majority of the O_2 demand (both BOD and COD) is caused by the presence of high concentrations of VFAs. BOD and COD concentrations decrease after the onset of the CH_4 fermentation phase and the conversion of VFAs. Landfill bioreactors have a higher BOD/COD ratio during the acid forming phase relative to conventional landfills (Reinhart and Al-Yousfi 1996; Reinhart and Townsend 1998). However, research suggests that this ratio decreases during the phase that follows (i.e., during the CH_4 fermentation phase (Phase IV)). After waste stabilization, COD may be influenced by high molecular weight organics such as humics and fulvics present in the leachate (Pohland et al. 1993). These residuals tend to elevate COD to a higher level than BOD and reduce the BOD/COD ratio. For instance, leachate BOD/COD ratios are usually higher than 0.5 for acid formation phases of decomposition but may decline to less than 0.1 for well-decomposed waste. It should be noted that COD is also influenced by an increase in the concentration of ammonia which has implications that are outlined later in this document.

2.4.2.1.5 Leachate Total Organic Carbon

Similar to the phenomenon observed for COD and BOD, the TOC levels increase after initial waste placement as a result of microbial solubilization of the organics. During the acid forming phase, TOC increases rapidly. An increase in TOC may also be observed soon after the introduction of waste containing high concentrations of organics. Because of the conversion of the VFAs to CH_4, TOC concentration tends to decrease during the CH_4 fermentation phase. TOC of conventional landfills has been reported to range between 30 and 30,000 mg/L (Pohland and Harper 1987; Krung and Ham 1991; Pohland et al. 1993; Chu et al. 1994; Kjeldsen et al. 2002). As an indication of the similarity in the decomposition mechanism, the TOC in landfill bioreactor systems ranges between 70 and 28,000 mg/L (Pohland et al. 1993).

2.4.2.1.6 Leachate Nitrogen Content

Nitrogen is mainly present in MSW leachate in the following forms: total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N). Ammonia is the most important of the three forms of nitrogen since at high concentrations (i.e.,1,500 - 2,500 mg/L) it tends to inhibit methanogens (Hashimoto 1986; Hansen et al. 1998) and therefore reduces the potential for waste degradation. Under anaerobic conditions, ammonia tends to accumulate in the leachate, especially when the leachate is recirculated. While the ammonia concentration in conventional landfills ranges between 2 and 2,200 mg/L (Krung and Ham 1991; U.S. EPA 2003), concentrations in landfill bioreactors range between 6 and 20,000 mg/L (Krung and Ham 1991; Pohland et al. 1993; Chu et al. 1994; Reinhart and Townsend 1998; U.S. EPA 2003). The accumulation of ammonia in the leachate from landfill bioreactors may adversely affect the methanogenic population. Ammonia concentrations of 1,500-3,000 mg/L are inhibitory to anaerobic processes at high pH levels, whereas concentrations above 3,000 mg/L can be toxic to most microorganisms in the waste (Pohland et al. 1993). Increasingly higher concentrations of ammonia in the leachate may indicate the potential for adverse effects on the methanogenic population, but these elevated values may also be an indication of an advanced stage of waste decomposition.

2.4.2.1.7 Leachate Metals and Metalloids Content

Heavy metals and metalloids exert toxicity to microorganisms influencing their biochemical activities, cell morphology, and growth (Hughes and Poole 1989; Gadd 1992; Jjemba 2004). Unlike organic compounds, metals do not degrade as the waste in the landfill decomposes, but rather they are transformed from one chemical state to another. Metals may also be precipitated under anaerobic conditions as carbonates, hydroxides, or sulfides; they may also bind to organic waste ligands. Metals can also be chelated or subjected to ion exchange within the landfilled waste matrix.

Most of what is known about metal transformations in landfills is based on chemical rather than biological analyses. Thus, there is limited information about the role of microorganisms on such transformations under the anaerobic conditions that are typical of landfills with progressively changing redox potential, moisture content, temperature, and pH. Beyond the adverse effects of metals in the leachate from a microorganism perspective, metals concentration in the leachate is an important parameter as it can affect the cost of off-site leachate treatment (e.g., a wastewater treatment plant may reject leachate if metals concentration (e.g., arsenic) is too high, thus causing the landfill to send the leachate elsewhere for treatment). The lower pH and higher organic content of the leachate during the initial landfill stabilization phases may mobilize some metals during the acid forming phase (Pohland et al. 1993). However, after the onset of the CH_4 fermentation phase, metal concentrations in the leachate tend to decrease. The decrease in these concentrations is a result of metal reduction, formation of metal sulfides, precipitation, and complexation within the waste matrix. Operators should recognize that the introduction of large concentrations of heavy metals, through either solid or liquids placed in the landfill, may retard or inhibit the solid waste degradation process and should be avoided in landfill bioreactors.

2.4.2.1.8 Semi-Volatile and Volatile Organic Compounds

SVOCs and VOCs may represent parameters that are of particular importance for monitoring as there is a potential for the introduction of complex organic constituents into the landfill, particularly when various industrial wastes are applied. The ability of microorganisms to assimilate and transform potentially toxic organic compounds in landfill bioreactors has been documented. For example, in-situ reductive dehalogenation of organic compounds (e.g., trichloroethylene and hexachlorobenzene) has been demonstrated in bench-scale landfill bioreactor studies (Kim and Pohland 2003). However, additional data are needed to compare and contrast the volatilization potential for specific VOCs and SVOCs that are most likely to appear in leachate for both conventional and bioreactor landfills.

2.4.2.1.9 Leachate Phosphate Concentration

The carbon to phosphate (C:P) ratio is important as the presence of low phosphorus quantities will slow down microbial growth and decomposition. A C:P ratio of 60:1 is deemed optimal for microorganisms to actively assimilate substrate carbon. Reducing the C:P ratio to this range in landfills may require adding commercial phosphorous-rich fertilizers together with the recirculation leachate. The beneficial effects of adding phosphates to laboratory-scale landfill bioreactor cells have been documented (Sheridan 2002). To the authors’ knowledge, this practice has not been further examined in the field.

2.4.2.2 Solids Monitoring

2.4.2.2.1 Refuse Composition

Cellulose and hemicellulose are the principal biodegradable components of MSW. While the anaerobic biodegradation of refuse in landfills requires the coordinated activity of several trophic groups of microorganisms, the conversion of cellulose and hemicellulose to CH_4 can be described by the following reactions:

$$(C_6H_{10}O_5)n + nH_2O \rightarrow 3nCO_2 + 3nCH_4 \qquad \text{Equation 2-2}$$

$$(C_5H_8O_4)n + nH_2O \rightarrow 2.5nCO_2 + 2.5nCH_4 \qquad \text{Equation 2-3}$$

The other major organic compound in refuse is lignin, which is, at best, only slowly degradable under the anaerobic conditions that prevail in landfills (Colberg 1988). In addition to its recalcitrance, lignin interferes with the decomposition of cellulose and hemicellulose by physically impeding microbial access to the more easily degradable carbohydrates. Thus, the complete conversion of cellulose and hemicellulose to LFG is not expected. Research to date from both field-scale and laboratory-scale systems has not established a lower level of cellulose and hemicellulose biodegradation as many components of waste contain cellulose, hemicellulose, and lignin and each waste component has unique biodegradation characteristics (Barlaz 2006).

The cellulose, hemicellulose, and lignin concentrations for a series of waste samples collected over the past 14 years are summarized in Table 2-5. Some of the samples represent fresh residential refuse while others were collected at a landfill. The samples collected at a landfill may not be comparable to the residential waste samples that do not include the large quantities of office paper or wood waste that are typically generated in the commercial and construction sectors, respectively. The relatively large range in cellulose, hemicellulose, and lignin concentrations is indicative of their variability in refuse composition. Unfortunately there is not a single factor to which this variability can be attributed. The last row in Table 2-5 represents values for the aggregate composition of waste entering a Canadian landfill. These values were calculated from measurement of the cellulose, hemicellulose, and lignin content of individual waste components and a waste composition survey. The composition of the aggregated waste stream includes some inert wastes that dilute the cellulose, hemicellulose, and lignin concentrations.

The precise composition of waste that enters a landfill is never known and can vary over time and with the landfill location (e.g., proximity to urban, residential, or rural waste streams). Nonetheless, it is generally agreed that the major sources of organic matter in landfills are paper, food waste, and yard waste. Of course, the disposal of yard waste in landfills is banned in many states, thus decreasing its importance as a source of CH_4 production. The U.S. EPA published an estimate of the composition of MSW based on the materials flow methodology (U.S. EPA 2006a). Using these data, coupled with data on the fraction of each MSW component that is recycled, it is estimated that paper makes up approximately 26.3 percent of the mass of MSW entering landfills. In that other waste streams (i.e., those that do not contain food waste, paper, and yard waste) are typically buried in landfills, the actual paper content in a landfill is lower than 26.3 percent. This is consistent with the lower cellulose content of waste entering the Canadian landfill as presented in Table 2-5.

Available data on the cellulose, hemicellulose, and lignin concentrations in fresh paper and wood waste are summarized in Table 2-6. It is noted that a relatively large difference in the cellulose content exists for the two office papers that were tested. The office paper described in Wu et al. (2001) had an ash content of 11.6 percent compared to a 1.4 percent ash content in the sample obtained by Eleazer et al. (1997). This difference is likely due to the presence of inorganic coatings in the sample obtained by Wu et al. (2001).

Table 2-5 Organic Composition of Fresh Residential Refuse (% of Dry Weight)

Reference	Cellulose (C)	Hemicellulose (H)	Lignin (L)	(C + H) / L	VS.	Source(6)
Ham and Bookter, 1982	42.4	nm	10.9	3.89	nm(5)	L
Jones et al., 1983(1)	25.6	6.6	7.2	4.5	59.6	L
Bookter and Ham, 1982(2)	63.4	nm	15.7	4.04	nm	L
Barlaz et al, 1989(3)	51.2	11.9	15.2	4.15	78.6	R
Eleazer et al. 1997	28.8	9	23.1	1.64	75.2	R
Rhew and Barlaz, 1995	38.5	8.7	28	1.68	nm	R
Ress et al., 1998	48.2	10.6	14.5	4.06	71.4	R
Price et al., 2003	43.9	10	25.1	2.15	nm	R
Barlaz unpublished(4)	22.4	5.8	11	2.57	nm	L

1. Refuse recovered from a landfill in the UK. The type of refuse and sampling strategy were not specified. The samples also contained 2.3% starch and 5% protein. Analyses were conducted using detergent fiber techniques.
2. Average of ten samples from the working face of a NY landfill.
3. The following additional analyses were performed on this sample: protein – 4.2%, soluble sugars – 0.35%, starch – 0.6% and pectin - <3%.
4. These values represent the composition of waste entering a Canadian landfill as described in the text.
5. nm = not measured.
6. (L) = landfill and (R) = residential refuse.

Table 2-6 Chemical Composition of Paper Products Present in Municipal Waste

Source	Newsprint		Office Paper		Corrugated Cardboard	Coated Paper	Branches
Reference	Wu et al. 2001	Eleazer et al. 1997	Wu et al. 2001	Eleazer et al. 1997	Eleazer et al. 1997	Eleazer et al. 1997	Eleazer et al. 1997
Cellulose	48.3	48.5	64.7	87.4	57.3	42.3	35.4
Hemicellulose	18.1	9	13.0	8.4	9.9	9.4	18.4
Lignin	22.1	23.9	0.93	2.3	20.8	15.0	32.6
Volatile solids	98.0	98.5	88.4	98.6	92.2	74.3	96.6

In summary, although the exact composition of waste that is buried in landfills varies, it is well established that the waste contains large concentrations of cellulose-containing materials. Paper is the major contributor to the cellulose and hemicellulose concentrations in landfills, followed by contributions from wood, yard debris and food waste. Therefore, regardless of initial concentrations of cellulose, hemicellulose, and lignin, it may be a useful measure of decomposition to track the relative changes in cellulose, hemicellulose, and lignin during the life of the facility.

2.4.2.2.2 Solids Monitoring Parameters

In the previous sections, discussions were presented regarding the physical and analytical measurements that can be made to demonstrate waste decomposition. Ultimately, it is the degradation of the waste solids themselves that is the true measure of decomposition. The values of the parameters presented in this section can vary widely due to heterogeneity of the waste, variations in the degree of decomposition, and moisture content. Unlike leachate and LFG sampling (where "weighted average values" may be obtained), it is physically difficult and expensive to obtain representative individual samples of waste for analysis. Table 2-7 presents suggested solids monitoring parameters for landfill bioreactors. More data from other bioreactor landfills regarding solids monitoring are needed; monitoring of the parameters shown in Table 2-7 (with the exception of moisture content) may not be necessary during routine operation.

Table 2-7 Landfill Bioreactor Solids Monitoring Parameters

Parameter	Method	Frequency	Optimum Range
Average Temperature	Thermometer	(1)	35 - 55 °C
Average pH (2)	U.S. EPA 9045C	(1)	6.5 - 7.6
Average Volatile Solids (percent M/M)(3)	U.S. EPA 1684	(1)	Decreasing Trend
Average Wet-Based Moisture Content (percent M/M)	-	(1)	< 45 %

Notes:
1. Frequency of solids monitoring should be determined on a site- and project-specific basis.
2. U.S. EPA, 2003.
3. Mehta et al., 2002.

2.4.2.2.3 Temperature

Temperature of the waste mass may be determined by thermocouples or thermistors within the waste mass and monitored electronically (via a data logging station) or by using portable meters. Temperature monitoring in bioreactor landfills operating aerobically is essential, as the regulation of temperature is critical to preventing elevated waste temperatures resulting from aerobic waste decomposition.

2.4.2.2.4 Volatile Solids

Adding moisture to the MSW stimulates biological activity in landfill bioreactors. This increase in biological activity may directly translate into an increase in the degradation of cellulose and hemicellulose, which may translate into a measurable increase in the rate of waste settlement. A three-year study at the Yolo County Landfill in California demonstrated that the abundance of cellulose, hemicellulose, and lignin are strongly correlated to the volatile solids (VS) content of MSW (Mehta et al. 2002). VS content in MSW is expected to decrease as the refuse decomposes because of cellulose and hemicellulose content loss from the waste. The main disadvantage of using VS as an indicator, however, is that, unlike cellulose, hemicellulose, and lignin, the analysis of VS offers a lower level of accuracy and is affected by daily cover application (Mehta et al. 2002).

2.4.2.2.5 Moisture Content

Moisture content of MSW should be examined to ensure relatively uniform distribution of the liquids that are added to the landfill bioreactor. The moisture content of the “fresh” incoming solid waste needs to be evaluated to calculate moisture addition requirements. Moisture addition requirements (i.e., volumes) will likely dictate the liquids addition rate required for landfill bioreactors.

2.4.2.3 Landfill Gas Monitoring Parameters

During the process of anaerobic solid waste decomposition, landfills generate significant quantities of CH_4 and CO_2. Both of these gases are undesirable greenhouse gases (Conrad 1995; Jjemba 2004), with CH_4 having a global warming potential approximately 20 times that of CO_2 (IPCC 2001). Controlling and monitoring the emissions of these gases is an essential element of any controlled landfill operation. Estimates of gas production rates in bioreactor landfills relative to conventional (i.e., Subtitle D) landfills vary, but previous investigations have indicated rates of landfill gas production at landfill bioreactors between two (Reinhart and Townsend 1998) and seven (U.S. EPA 2005b) times higher than that at conventional landfills. As a result, it is critical to design gas collection systems at landfills operating as bioreactors to capture the expected additional LFG. The rate and quantity of LFG generated is dependent on the mass and composition of waste as well as the moisture conditions within the landfill. Equation 2-4 describes the relationship of the predicted CH_4 generation over time with regard to the composition of the waste, disposed waste mass, and time.

$$Q_{CH_4} = L_o R\left(e^{-kc} - e^{-kt}\right) \qquad \text{Equation 2-4}$$

Where:

Q_{CH4} = methane generation rate at time t (m^3/yr);
L_o = methane generation potential of the waste (m^3 CH_4/Mg waste);
R = average annual refuse acceptance rate during the active life of the landfill (Mg/yr);
k = methane generation rate constant (yr^{-1});
c = time since landfill closure (yr) and
t = time of initial waste acceptance (yr), respectively.

As will be discussed later in chapter 5, LFG generally consists of approximately 50 percent CH_4 and 50 percent CO_2 by volume, so to calculate the total LFG generated at a specific time, Equation 2-4 should be multiplied by 2.

Of particular interest when assessing LFG generation with regard to landfill bioreactors are the parameters L_o and k. The capacity to generate CH_4 generally depends on the organic content and moisture content of the waste (U.S. EPA 1998). As described previously, operation as a landfill bioreactor by increasing moisture content of the waste may accelerate the decomposition of the waste and therefore increase the value of k. These parameters can be estimated on a site-specific basis and implemented in the Landfill Gas Emissions Model Version 3.02 (LandGEM), developed by U.S. EPA, to predict LFG generation based on waste placement data and kinetic parameters. Since landfills operated as bioreactors are expected to generate LFG at a greater rate than dry tomb landfills, gas recovery systems at landfill bioreactors need to be designed to handle larger flow rates than those at conventional landfills.

The discussion thus far has mainly been on the anaerobic reactions that occur in landfill bioreactors. It is recognized that landfill bioreactors can be operated as aerobic units by the controlled introduction of air into the waste after placement. Potential issues regarding air addition in bioreactor landfills include hydraulic limitations as well as subsurface fires. Jain et al. (2005) found that leachate recirculation had a significant impact on the air permeability of MSW. One of the regulatory concerns associated with aerobic landfill bioreactors has been the potential for subsurface fires from spontaneous combustion. Literature suggests that carbon monoxide (CO) production may be an indicator of subsurface fires (U.S. EPA 1998). The U.S. EPA's Compilation of Air Pollutant Emission Factors (AP-42) cites a default CO concentration of 142 ppm for MSW landfills; however, it is noted that this value was based on data collected from a limited number of sites, and the data were classified with a qualifier of "poor" (U.S. EPA 1998). A study at a landfill undergoing leachate recirculation and air addition in Florida found CO concentrations between 0-30 ppm in areas operating under anaerobic conditions, and CO concentrations up to 1,200 ppm in areas operating under aerobic conditions (Powell et al. 2006). However, areas showing higher CO concentrations did not have elevated temperatures indicative of a subsurface fire. A combination of CO and temperature monitoring is likely the most effective approach in evaluating the presence of subsurface fire.

MSW landfills with an actual or design capacity equal to or greater than 2.5 million Mg of waste (or 2.5 million m^3) are subject to New Source Performance Standards (NSPS) for air emissions, which require the collection of LFG and 95% destruction (by weight) of non-methane organic compounds (NMOCs), a class of compounds that depletes stratospheric ozone, contributes to global warming, and includes hazardous air pollutants (HAPs). Currently, specific regulations regarding anaerobic landfill bioreactor LFG collection requirements are found in 40 CFR Part 63, Subpart AAAA. As a result of these requirements, landfill bioreactor facilities must comply with LFG collection requirements sooner than dry tomb landfills. Because of limited data available for LFG emissions at aerobic landfill bioreactors, these systems are regulated in a similar manner to dry tomb landfills under NSPS. The compounds included in the monitoring program and the monitoring frequency may be determined on a site-specific basis and guided by local, state, and federal regulations pertaining to the site or by the goals of the landfill bioreactor owner/operator.

Chapter 3. Site Description and Analytical Methods

3.1 Site Description and System Design

The OLRDF is located in Louisville, Jefferson County, Kentucky. The site, shown in Figure 3-1, is located on the north side of Outer Loop Road, immediately west of Interstate 65 with an approximate area of 316 hectares (780 acres). The site comprises eight landfill units, designated Units 1 through 8. Units 1, 2, 3, and 6 are inactive. Unit 4 is an active, permitted C&D debris landfill. Unit 8 is an active bioreactor landfill unit that is located to the north of Unit 7 and overlays parts of Units 7 and 4 (not shown in Figure 3-1). Waste placement in Unit 8 just started and will not be discussed in this report. The focus of this study is on portions of Unit 5 and Unit 7, which are both Subtitle D landfill cells; Unit 5 did not receive any waste during the study, while portions of Unit 7 received waste until 2005, as described later. The landfill bioreactor permit approval for this site was received from the Commonwealth of Kentucky, Kentucky Natural Resources and Environmental Protection Cabinet, Department for Environmental Protection in 2001 under Permit No. 056-00028.

The OLDRF is owned and operated by WM and has been used for waste disposal for approximately 35 years. The site is situated within the alluvial valley of the Ohio River; approximately nine miles southwest of River Mile 614. The area is generally flat with elevations averaging 139 m (456 ft) above mean sea level (MSL). The region is effectively enclosed by topographically elevated areas on the west, east, and south. Elevations range up to 229 m (750 ft) above MSL in areas surrounding the site. Topography and stream development in the area have been modified by construction and development activities of the region. Because of the flat topography, the clayey nature of the soil, and the relatively low elevation, the area is naturally poorly drained. To enhance surface drainage for the development of the region, several engineered drainage channels have been constructed in the vicinity of the landfill. The channels drain toward the southwest, eventually discharging into the Ohio River. Some of the cells on the site are unlined and the entire site utilizes pumps to provide an inward gradient to groundwater flow into the site.

The average yearly regional temperature is 13º C (55° F), ranging from -30 to 40º C (-21 to 103° F). Average annual precipitation is approximately 113 cm (44 in.) of rainfall, plus approximately 38 cm (15 in.) of snow (U.S. Department of Commerce 2004). The average number of days with precipitation is 125 annually, with 47 days being associated with thunderstorms. The prevailing wind in the area is generally from the south. Details regarding the meteorological conditions at the site, with particular focus on precipitation as it relates to the moisture balance analysis at the site, will be presented in later sections.

In contrast to some of the landfill bioreactor research described in Chapter 2, the demonstrations at the OLLB are large-scale research efforts at a full-scale operational landfill. The study covers a total of approximately 20.2 hectares (50 acres) in lined landfill units. In this study, three types of landfill units were studied. The first unit was a control that was developed and filled as a conventional Subtitle D landfill without any intent of supplemental liquid addition (Control cells). The second type of unit in this study was a landfill that had a piping network (for liquids and air addition) installed as waste was being placed (As-Built landfill bioreactor cells). The third was a Subtitle D landfill that was retrofitted with a moisture addition piping network to allow the recirculation of liquids (Retrofit landfill bioreactor cells). Each of the three units was divided into subcells to provide a quasi-“duplicate” of the test cell, which will be discussed in more detail in subsequent sections.

3.1.1 Control Landfill Cells

3.1.1.1 General

Unit 7 is located in the western portion of the OLDRF as shown on Figure 3-1. Portions of that Unit, designated 7.3A and 7.3B, have been designated as the Control cells for the study. These cells have been operated as conventional Subtitle D (i.e., dry tomb) landfills since initial waste placement began in 1998.

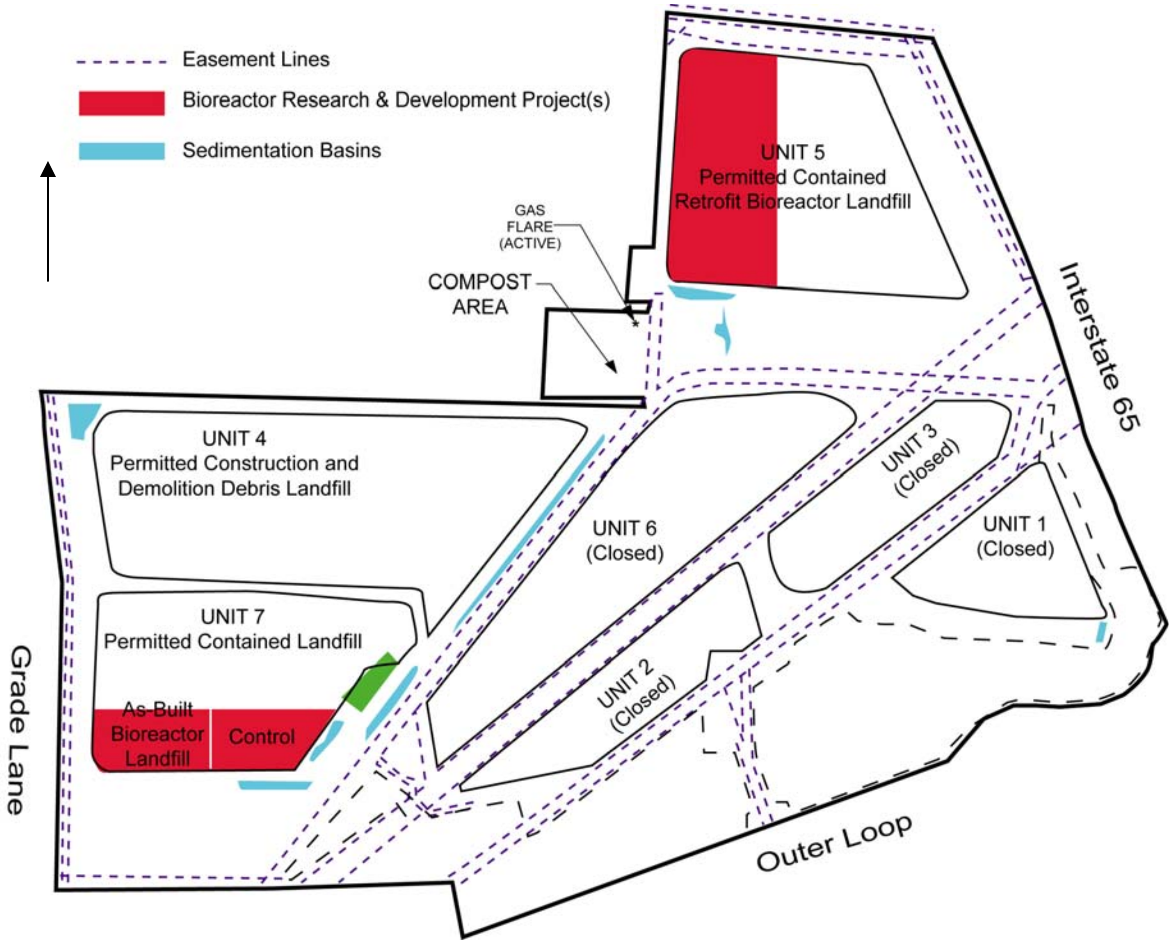


Figure 3-1 Outer Loop Landfill Site Map

The cells were monitored and sampled in a similar manner to the landfill bioreactor units. The Control cells consist of two paired landfill cells (i.e., Control cell A and Control cell B) that are not hydraulically separated. However, a barrier layer was installed between the Control and As-Built units. The layer consists of low permeability clay along with an additional layer of permeable tire chips.

The Control cells were selected to represent waste decomposition in a conventional Subtitle D landfill without liquids addition and with standard vertical LFG extraction wells. Waste placement in the Control cells commenced in 1998 and ceased in 2004. At the start of the landfill bioreactor project in 2001, solid waste in the Control cells was approximately three years old. Prior to the start of the project in 2001, approximately 342,000 Mg (380,000 tons) of solid waste was present in the Control cells. Additional waste was placed in Control cell A and Control cell B during the project to bring the cells to final grade.

3.1.1.2 Leachate Collection System (LCS)

The Control cells were lined with a smooth 60 mil HDPE geomembrane on the base areas while textured 60 mil HDPE geomembrane was used on the perimeter slopes (2.5H:1V). A 10 oz. non-woven geotextile cushion layer was placed over the bottom liner and a double-sided geocomposite was placed over the side slope. A 0.3 m (1 ft) granular leachate drainage blanket covered the base areas, and was constructed with non-carbonate coarse gravel. In swales in the valleys in the Control cells, an 8 in. standard dimension ratio (SDR) 11 perforated HDPE pipe was laid on a gravel bed then covered with gravel. This coarse ¾ in. to 1 ½ in. gravel material had the same basic characteristics as the remainder of the leachate drainage blanket, except it was a larger grade. Each leachate collection line terminated on the west side of the Control cells into a sump underlain by the composite liner system. A pumping system was installed at each sump, which provides a means to pump leachate that accumulates. These pumping systems discharge into a force main that terminates at the site's leachate treatment plant.

3.1.1.2 Gas Collection

As with any "dry tomb" landfill cell, each Control cell contained two vertical gas collection wells installed in the center of the solid waste mass. LFG collection wells were connected to header lines that connect to the flare station. The LFG collection headers maintained separate gas collection fields in the Control cell. The first gas collection header collects landfill gas mainly generated in Control cell A, while the second collects the gas generated in Control cell B. Before merging together, gas flow in each header line is measured via an orifice plate installed within the pipe. A probe was also installed in each gas collection well to allow for LFG sample collection, as will be discussed in Section 3.3.

3.1.2 As-Built Landfill Bioreactor Cells

3.1.2.1 General

The As-Built cells are also located within Unit 7, designated 7.4A and 7.4B, as shown in Figure 3-1. The cells were *designed* as a sequential aerobic-anaerobic landfill bioreactor (also referred to as "hybrid"). The rationale behind the sequential approach was to promote the rapid decomposition of easily degradable organic matter in the aerobic stage of treatment with the intent of reducing the amount of fermentable organic matter entering the anaerobic stage. This strategy may shorten the acid-generating phase of anaerobic waste decomposition and result in a more rapid onset of methanogenesis. Thus, the objective of these cells was to examine the impact of increased moisture content and waste aeration on the degradation of recently placed MSW. It is noted that the aim of this research is not to examine the performance of WM's patented design (U.S. Patent No. 6,283,676 B1) but rather the effect of liquid addition and sequential aerobic/anaerobic operation on the solid waste degradation.

The As-Built cells were divided to provide quasi-"duplicates" that are hydraulically separated with a clay barrier [0.3 m (1 ft)]. A layer of shredded tires was placed onto the clay barrier to act as a conduit for leachate to reach the bottom liner. The placement of shredded tires was discontinued in the first quarter of 2004 since the layer acted as a conduit for LFG and rainwater migration. A schematic of the configuration discussed here is presented in Figure 3-2.

The initial waste placement in As-Built cell A and As-Built cell B occurred during June and October of 2001, respectively as presented in Figure 3-3. As of June 2005, approximately 1,461,000 Mg (1,610,000 tons) of solid waste had been placed in the two As-Built cells [i.e., 590,000 Mg (650,000 tons) in As-Built cell A and 871,000 Mg (960,000 tons) in As-Built cell B]. The cells were constructed in 4.6 m (15 ft) vertical lifts for a total of seven different lifts. Based on mass, solid waste comprised approximately 71 % while biosolids from a municipal wastewater treatment plant, C&D debris, and soil accounted for approximately the remaining 13%, 9.2% and 6.8%, respectively.

3.1.2.2 Leachate Collection System

Since the As-Built cells are a part of Unit 7, the LCS is similar to that of the Control cells as described in section 3.1.1.2. Each leachate collection line drains into a separate sump underlain by the composite liner system. A pumping system was installed at each sump, which provides a means to pump leachate from each sump as it accumulates to a designated depth. As with the Control cells, these pumping systems discharge into a force main that terminates at the site's leachate treatment plant.

3.1.2.3 Piping Network Installation

The design of the As-Built cells liquid addition, air injection, and LFG extraction piping network utilized one piping network for delivering liquids and a second piping network for distributing air and extracting LFG. The sequence and method of placing the pipes is described below.

The first 4.6 m (15 ft) thick lift of waste was placed on top of the leachate collection system, followed by placement of the first pipe layer (comprised of 10.2 cm (4 in.) ID perforated HDPE) on the top surface of the first lift. The pipes were placed at approximately 18.5 m (60 ft) wide intervals across the top surface of

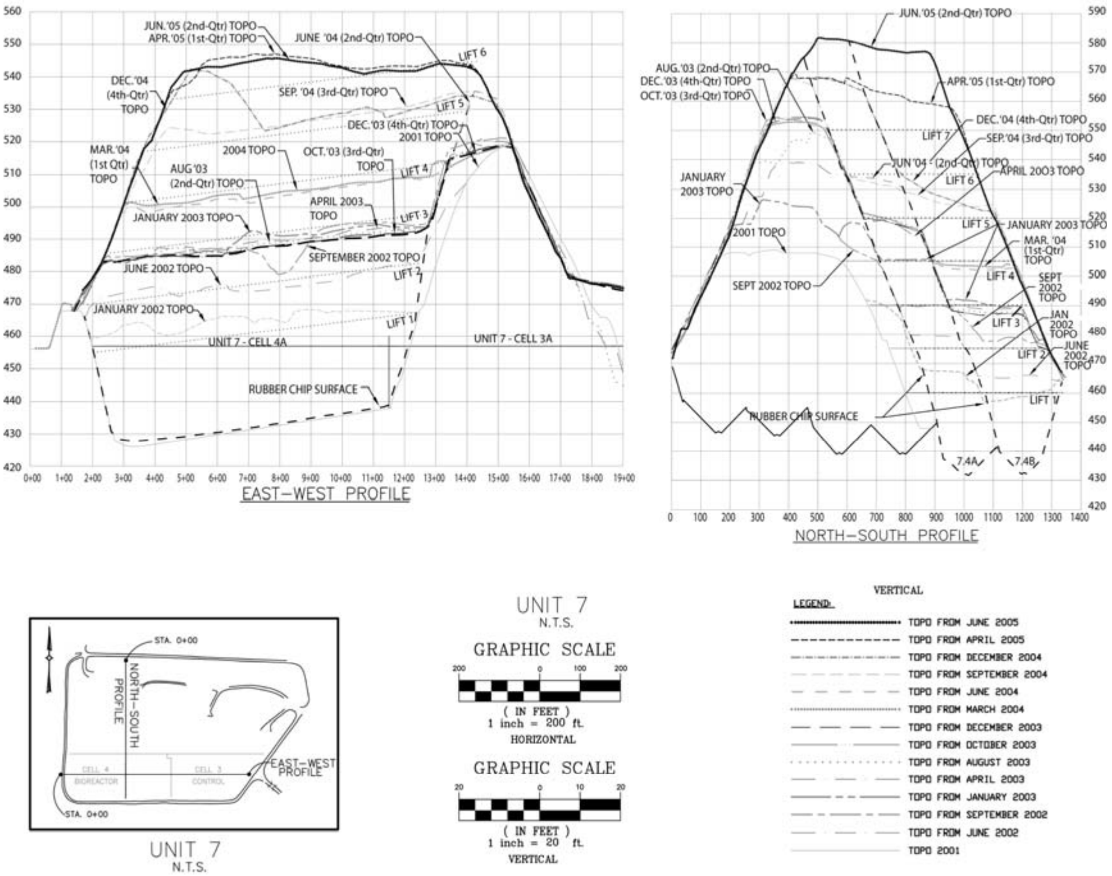


Figure 3-2 Solid Waste Placement in the As-Built Landfill Bioreactor Cells

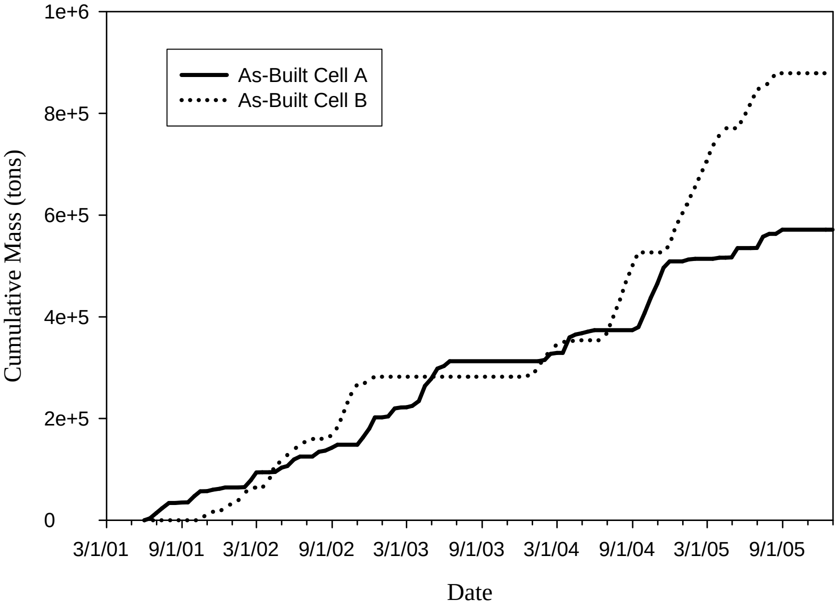


Figure 3-3 Solid Waste Placement in As-Built Landfill Bioreactor Cells

the waste. The length of these pipes was dependent on the length of the individual lift within the cell. The pipes were perforated with three 1 cm (0.4 in.) diameter holes at 120° intervals around the pipe, with holes spaced at 0.3 m (1 ft) intervals along the length of the pipe. The pipes were covered with a permeable media generally consisting of tire chips; however, an alternative design was introduced in the second quarter of 2004 that involved placing a thin horizontal layer of permeable material on top of each lift to facilitate liquid recirculation, air addition, and LFG collection. Each end of the perforated piping has a section of solid pipe of the same diameter that is subsequently connected to a common 10.2 cm (4 in.) ID manifold pipe. After placement and installation of the first lift and pipe layer, a second lift was placed, followed by a second piping layer. In this design, the uppermost lift of waste is aerated, while the lift immediately below this lift receives liquid, and LFG is extracted from all deeper lifts.

3.1.2.4 Air Introduction

Air addition began once a completed lift was placed on top of the piping layer (e.g., the second lift was aerated by injecting air through the first layer of piping). Each 4.6 m (15 ft) lift of waste received injected air beginning approximately 30 days after lift placement. This was accomplished by connecting the header pipe for a particular lift to a high-volume air compressor. Compressed air was continuously pumped into each new lift at a maximum rate of 57 m^3/min (2,000 ft^3/min) for a period ranging from 30 to 90 days. The following three set points were designated as the threshold points for the cessation of air introduction: (i) waste mass temperature of 71 °C (160 °F); (ii) net change in waste mass temperature of 6.7 °C (12 °F) within 24 hours; and/or (iii) after 90 days of air introduction. Set points (i) and (ii) were established to prevent elevated waste temperatures and potential subsurface fire caused by aerobic decomposition. In all cases, air introduction stopped whenever one of these set points was reached. Until January of 2006, 9.6×10^7 m^3 (3.4×10^9 ft^3) of air was injected into As-Built cell A while 4.8×10^7 m^3 (1.7×10^9 ft^3) of air was injected into As-Built cell B. Based on the total mass of solid waste placed in the cells, As-Built cell A received almost five times more air per unit mass of waste [162 m^3/Mg (6,300 ft^3/ton)] compared to As-Built cell B [32 m^3/Mg (1,260 ft^3/ton)].

3.1.2.5 Liquids Addition

Liquids addition into the As-Built cells was accomplished through the piping network previously described. Liquids were gravity-fed through one of four on-site tanks to the lift of waste directly below the lift being aerated. The addition of liquids was controlled and included intermittent dosing depending on several daily and seasonal factors including the apparent moisture content of the in-place waste, forecasted precipitation events, and recent moisture additions.

Liquids added into the As-Built cells included a combination of industrial liquids as well as recirculated leachate obtained from other lined units at the OLDRF site. The industrial liquids added to the As-Built cells consisted mainly of beverage waste (75 percent); oily wastewater (10 percent); paint waste (9 percent); ink water (2 percent); and other (4 percent). Volumes and chemical properties of the industrial liquids are presented in Table 3-1. A summary of the liquids injection history as related to moisture balance in the As-Built cells is provided in Section 4.2. Figures 3-4 and 3-5 present the volume of industrial liquids added to As-Built cell A and As-Built cell B, respectively. Figures 3-4 and 3-5 show that the majority of industrial liquids were added to the As-Built cells after March 2004.

Table 3-1 Chemical Properties of Industrial Liquids

Liquid Type	State	Percent of Total[1]	pH	BOD (mg/L)	COD (g/L)	NH_3-H (mg/L)
Beverage waste	Liquid	75	NA	NA	NA	NA
Oily wastewater	Liquid	10	5.7 – 8.1	NA	19 – 134	1 - 95
Paint waste	Liquid & Sludge	9	5.0 – 9.1	NA	2.4 – 16	1 - 550
Ink water	Liquid	2	9.9	NA	38	163
Food waste	Liquid & Sludge	1	4	1,800	33	NA
Other (septic, municipal, food, beverage, cleaning)	Liquid & Sludge	3	3.6 -7	NA	NA	NA

1: This represents the approximate percentage of the total industrial liquids added to the As-Built cells.

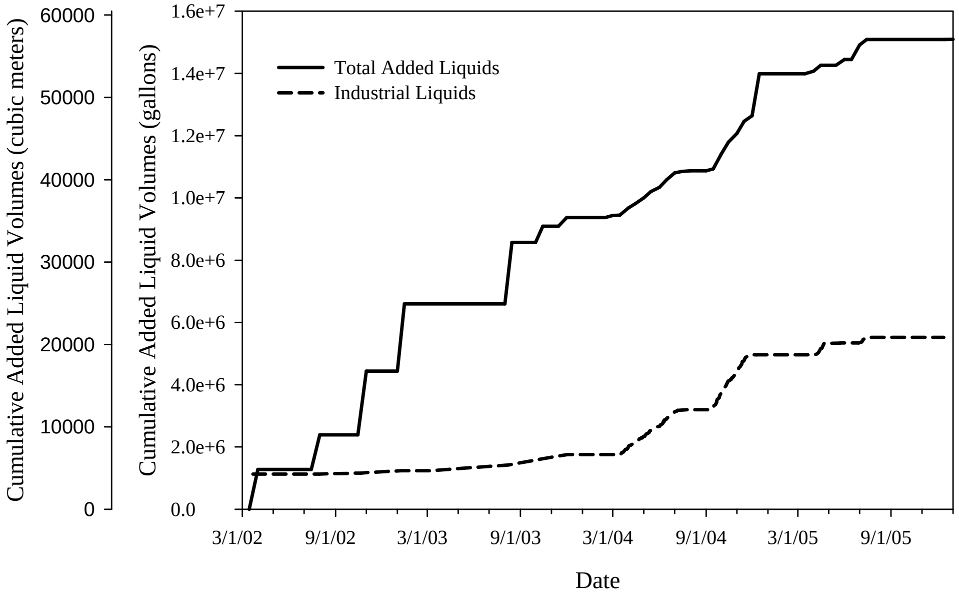


Figure 3-4 Cumulative Industrial and Total Added Liquids in As-Built Cell A

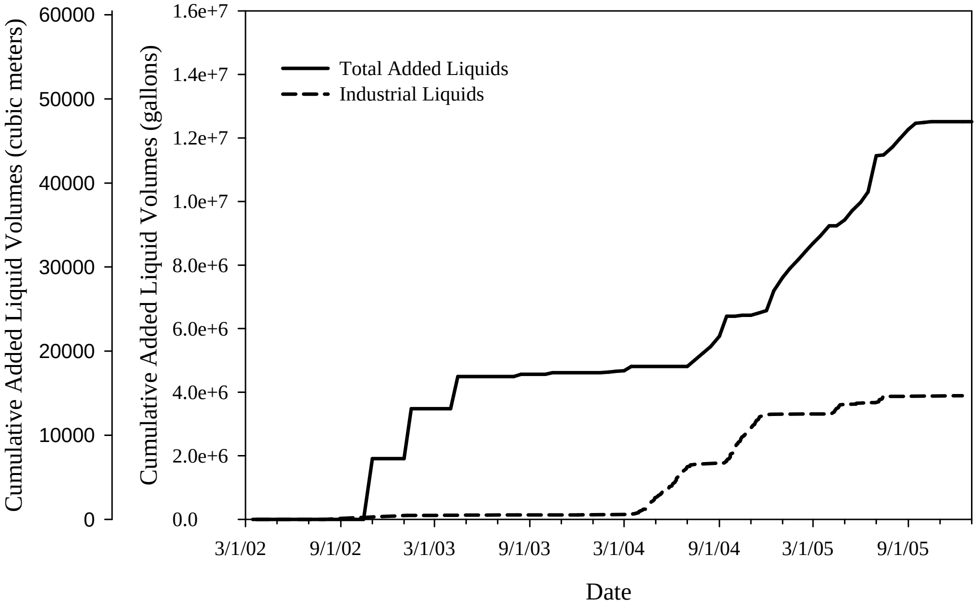


Figure 3-5 Cumulative Industrial and Total Added Liquids in As-Built Cell B

3.1.2.6 Gas Collection

LFG was collected in deeper waste lifts through the pipes previously utilized for air addition. In general, a series of LFG collection pipes were connected to the active gas collection system once air addition and liquids addition were no longer occurring in a particular lift. The LFG collection started in April of 2003 for the As-Built cells.

3.1.3 Retrofit Landfill Bioreactor Cells

As part of this research, an existing “dry tomb” MSW landfill cell was retrofitted with a piping network to operate as a bioreactor landfill cell. Apart from the main objective of examining the effect of liquids on solid waste degradation, research in the cell aimed to assess the effects of nitrate-enriched leachate on landfill bioreactor performance. Previous research concluded that leachate recirculation was shown to increase the ammonia concentration within landfill bioreactor cells. Ammonia rich leachate from the OLRDF was treated in a sequencing batch reactor aerobically to convert ammonia to nitrate. This leachate containing nitrate was then recirculated in the Retrofit area. As nitrate-containing liquid moves through the upper sections of the landfill bioreactor cells, denitrifying bacteria convert nitrate to N_2 gas, resulting in a net loss of nitrogen from the landfill.

The Retrofit bioreactor landfill Unit (Unit 5) is located in the northern portion of the OLRDF complex, as shown in Figure 3-1. The Unit consists of four separate landfill subcells (designated 5.1A, 5.2A, 5.1B and 5.2B) and is permitted as a Subtitle D cell with a single composite clay liner. Each subcell is equipped with its own leachate collection line, which allows sampling at each distinct leachate sump. To provide for hydraulic separation between the test areas and because of geometric similarities, Unit 5.1A (the most southern cell, referred to as Retrofit cell A) and Unit 5.2B (the most northern cell, referred to as Retrofit cell B) were selected for this study. Liquid introduction also occurred in the two middle cells of the Retrofit unit (5.1B and 5.2A) as will be discussed later. Leachate analysis results presented in Section 4.4 is for the leachate collected from the sump of cell 5.1A and 5.2B (referred in Section 4.4 as Retrofit cell A and Retrofit cell B, respectively).

Waste placement was initiated in July 1995. Approximately 1,752,000 Mg (1,931,000 tons) of solid waste were in place by October 1997, of which 32 percent was special waste consisting mainly of contaminated soils, while the remaining 68 percent was MSW. Between October 2000 and March 2001, an additional 136,000 Mg (150,000 tons) of MSW was placed in the cell to adjust the final top deck elevations as presented in Figure 3-6. During 2004, daily cover material was stockpiled on the western side of the cell, as presented in Figure 3-6. Since the cell did not receive new waste during the study, a 1 m thick long-term clay cover was placed on the Unit. A 5 cm thick layer of cover soil was then placed on top of the clay cover and the cell was seeded with grass for erosion control.

3.1.3.1 Leachate Collection System

The LCS consists of a collection layer (Figure 3-7), separator geotextile, collection pipe, and cleanout riser. The collection layer consists of a 0.3 m (1 ft) thick layer of sand on the 10H:1V cell floor and 2H:1V intercell berms, and geocomposite on the 3H:1V perimeter berms. Perforated pipes used to collect the leachate were surrounded with coarse aggregate and wrapped by a nonwoven geotextile. The collection pipes discharge via perforations in the pipe into the Retrofit cell’s sumps. Also, collection pipe cleanout risers connect to the collection pipes in the cell sumps. The pumped discharge from the sumps is connected into the site’s leachate management system via a force main. Underlying the LCS in the Retrofit unit is a geomembrane that was constructed of 60 mil HDPE that was smooth on both sides.

3.1.3.2 Liquids Addition

Construction of the Retrofit bioreactor cells took place between March and May 2001 and included installation trenches, moisture distribution and gas collection piping, thermocouples, and ORP probes. To increase the moisture content of the Retrofit cells, 26 horizontal infiltration galleries were constructed. The trenches were 4.6 to 6 m (15 to 20 ft) deep, 1 m (3.3 ft) wide and were constructed just below the surface of the landfill (Figure 3-8). The trenches were spaced approximately 18.3 m (60 ft) apart as presented in Figure 3-8. Each trench contains two 7.6 cm (3 in.) ID HDPE pipes, one for liquid introduction and the other for gas collection. Each pipe was perforated with 0.95 cm (0.4 in.) holes every 0.3 m (1 ft) along the length of the pipe. The trenches were bedded with tire chips and backfilled with permeable material like shredded tires to allow for liquid and gas flow as illustrated in Figure 3-8. The liquid introduction lines were then connected through a solid 7.6 cm (3 in.) ID riser pipe to a valve and then to an HDPE liquid distribution header. Temperature and ORP probes were also installed at the end of each horizontal trench.

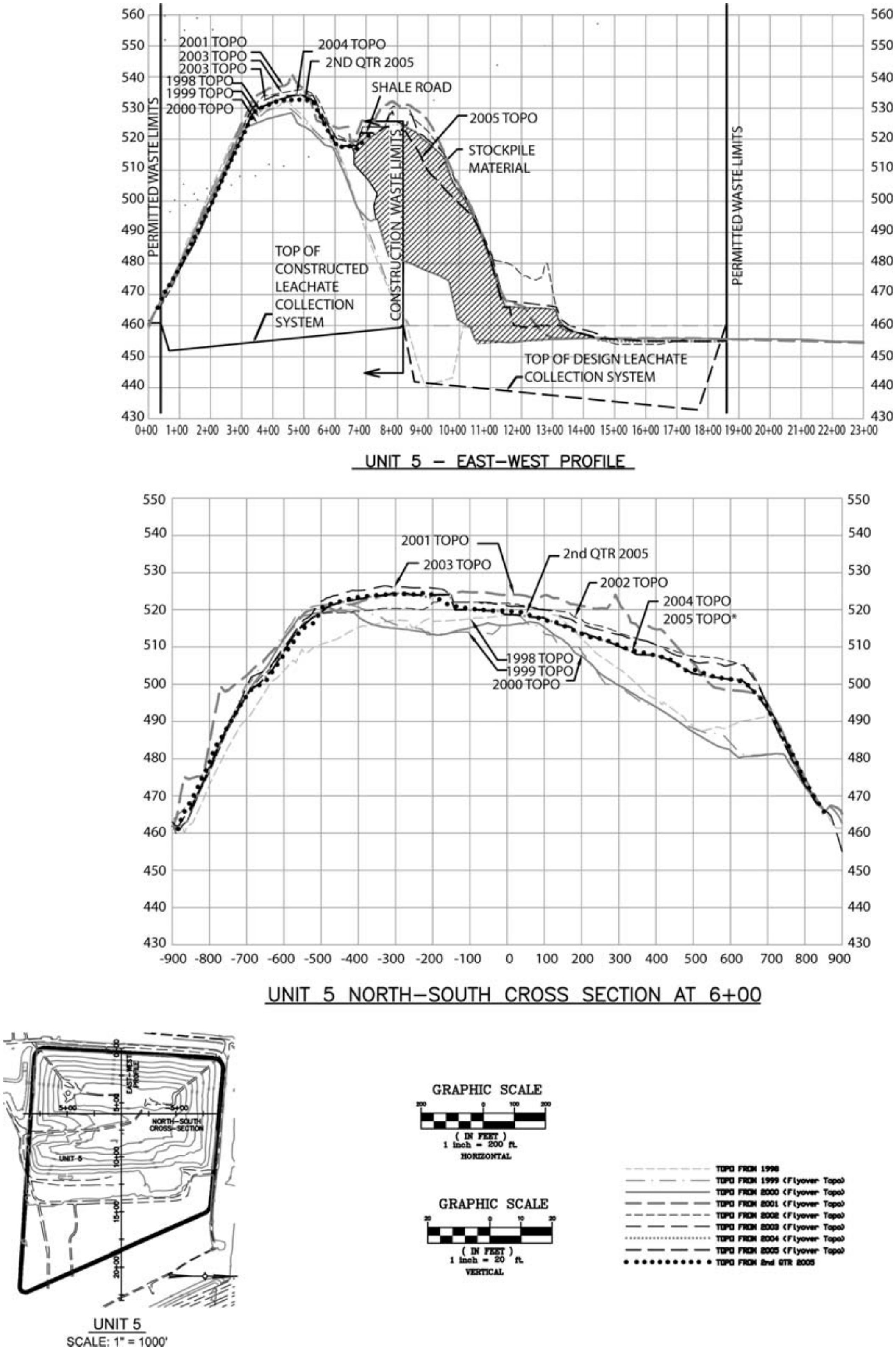


Figure 3-6 Solid Waste Placement in the Retrofit Landfill Bioreactor Cells

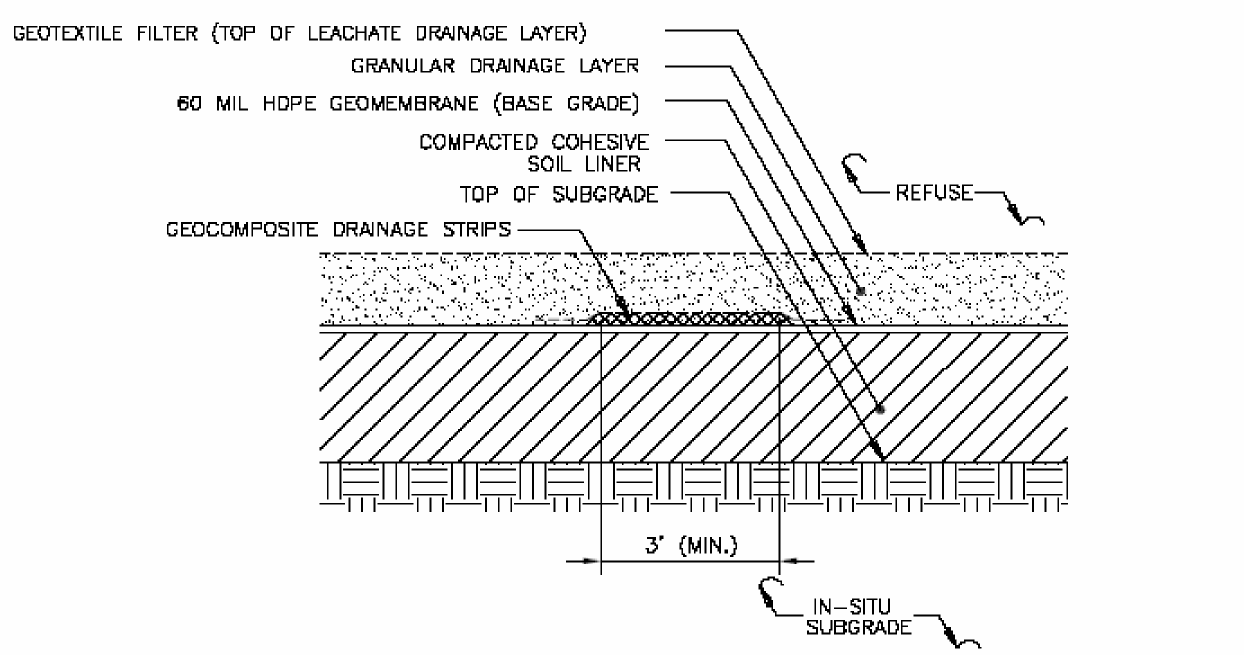


Figure 3-7 Bottom Liner Configuration of the Retrofit Unit

Nitrified leachate was added intermittently depending on daily and seasonal factors, apparent moisture content of the in-place waste, forecasted precipitation events, recent moisture additions as well as operator judgment. The ultimate goal was to achieve uniform infiltration while avoiding leachate outbreaks, seeps, and the reduction of performance of the LFG collection. Initial liquid introduction commenced in March 2002 and additions occurred steadily until October 2002 when liquid introduction stopped for a period of about 10 months. During that time, no liquids were added to the cells except for limited amounts of infiltration from precipitation through the long-term cover system. After this 10-month period, the injection episodes continued until spring 2006 (with the exception of a 4-month period between January 2005 and April 2005). The cumulative liquids injection is presented in Figure 3-9, and is discussed in more detail in Section 4.2.

The main source of moisture added to the Retrofit cells was nitrified leachate which was treated ex-situ by chemolithotrophic bacteria that converts NH_4^+ to NO_3^- as presented in Equation 3-1.

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

Equation 3-1

Laboratory research suggests that denitrifying bacteria that are already present in the waste mass will utilize the NO_3^- as a terminal electron acceptor to form both N_2 and small amounts of N_2O gases. Liquid sources other than leachate, including water from the landfill underdrain, sedimentation pond, and other liquid waste streams as allowed by the permit, were used to augment the supply of leachate. These liquid sources were pumped from the sequential batch reactor (SBR) pretreatment plant to holding tanks that were then used to distribute leachate to the trenches via a force main and manifold system.

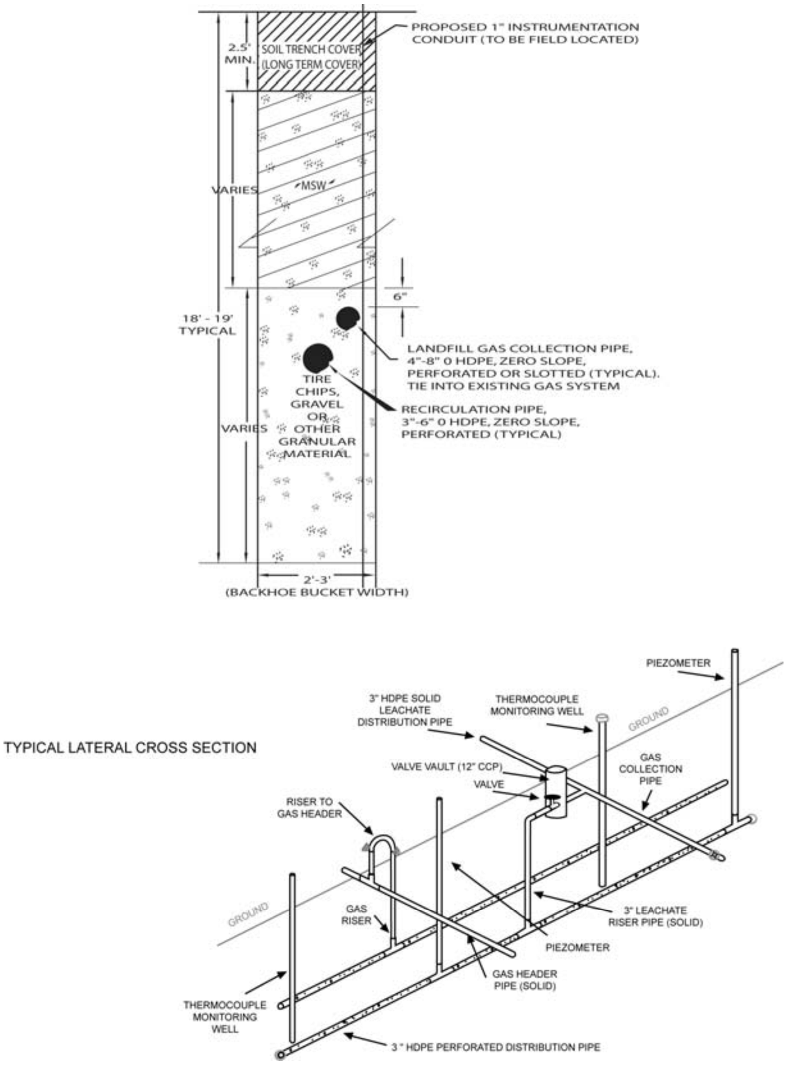


Figure 3-8 Cross-Sectional Layout of Liquid Introduction Trench

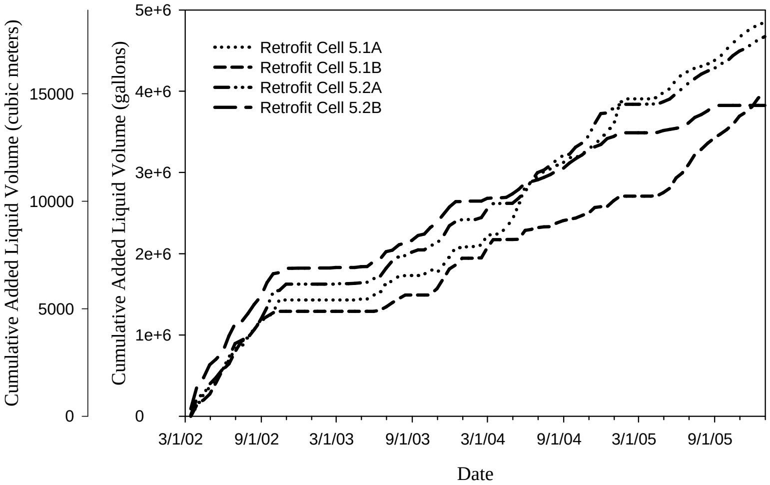


Figure 3-9 Cumulative Liquid Introduction into Retrofit Bioreactor Landfill Unit by Subcell

3.1.3.3 Gas Collection

In addition to the horizontal gas collection trenches discussed previously, there are 17 vertical gas collection wells installed in the Retrofit cells, as shown in Figure 3-10. These vertical LFG collection wells served the dual purpose of collecting LFG and penetrating layers of daily soil cover. Probes for measuring temperature and ORP were installed during vertical gas well installation in 2000. Additional thermocouples and ORP probes were installed during 2001 when the Retrofit cells were retrofitted with the additional gas collection and the liquid distribution piping network.

LFG collection wells and trenches were connected to two header lines that connect to the flare station. The LFG collection headers maintained separate gas collection fields in the Retrofit unit. The first gas collection header collects landfill gas mainly generated in cells 5.1A and 5.1B, while the second collects the gas generated in cells 5.2A and 5.2B. Before merging together, gas flow in each header line can be measured via an orifice plate installed within the pipe. A probe was also installed in each header pipe to allow for LFG sample collection, as will be discussed in Section 4.3.

3.2 Sample Procedures and Methods

The primary objective of this research was to assess the effect of liquids addition on waste decomposition. The type and frequency of each analysis follows most of the guidelines presented in Chapter 2, as well as in the First Interim Report. A discussion is presented herein of the sampling locations and sample handling and analysis protocols. Methods used in the project meet specifications for U.S. EPA-approved methodologies and are appropriate for the parameter and matrix of interest. The methods are generally either from SW 846 (U.S. EPA 1996) or Standard Methods for the Examination Water and Wastewater (APHA 1999). Equipment used for field sampling is calibrated and maintained according to manufacturer's guidelines. Redundant solid waste probes (i.e., temperature and ORP) were employed to circumvent any premature instrument failure. Collected leachate samples were placed in a cooler and maintained at 4 ˚C (40 °F) using crushed ice and were shipped overnight to the appropriate laboratory for analysis. During the study, inclement weather and component equipment failure affected sampling frequency and the sampling periods were altered to accommodate such occurrences.

3.2.1 Leachate Sampling

Leachate was collected monthly from each of the landfill bioreactor and Control cells. The design of the landfill units (i.e., paired cells) was such that, with the exception of the Control cells, each cell was hydraulically separated at the base from the surrounding cells. The Retrofit cells were separated by approximately 305 m (1,000 ft) laterally. The As-Built cells were constructed with a clay barrier to hydraulically separate As-Built cell A and As-Built cell B.

Leachate samples were collected directly from the tap on the leachate riser line for each subcell. Switching the riser pump from automatic mode to manual mode (i.e., turning the pump on manually) prior to purging and sampling was shown to be an effective method for obtaining an adequate volume of leachate. Leachate sample bottles were collected in the following sequence: COD, BOD, VFAs, pH, temperature, VOCs, SVOCs, TKN, ammonia-N, nitrate-N, nitrite-N, metals, calcium, sodium, ortho phosphate, total phosphate, chloride, sulfate, TOC, DOC, TDS and specific conductance. Methods used to analyze for these parameters are presented in Table 3-2, while the list of VOCs and SVOCs examined are presented in Tables 3-3 and 3-4, respectively. To obtain a representative sample, effluent was purged prior to actual sample collection in accordance with the approved sampling protocol in the QAPP.

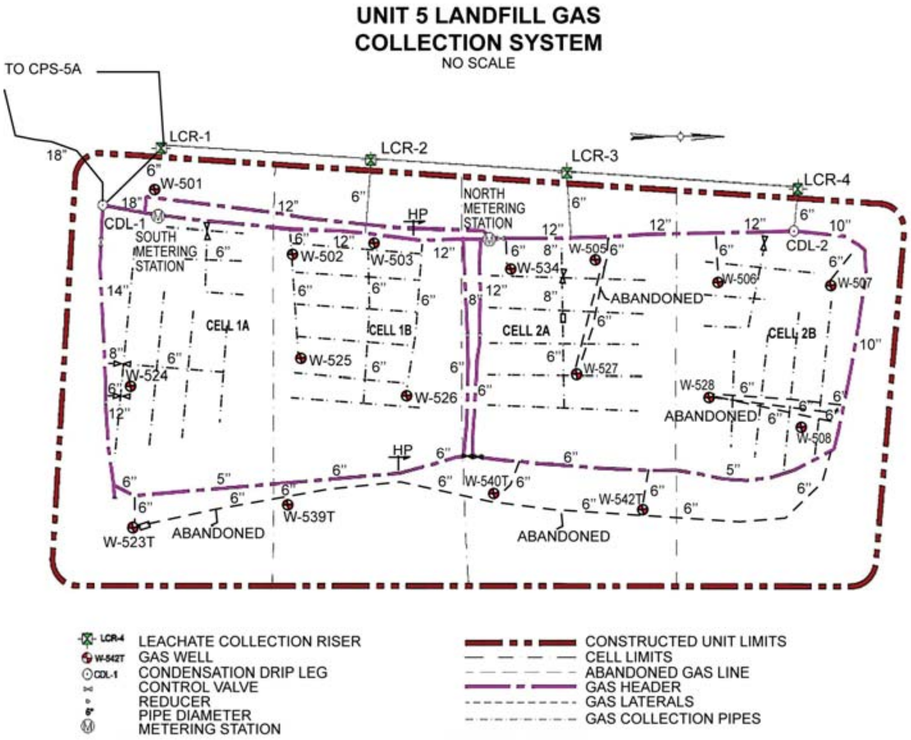


Figure 3-10 Liquid Introduction and Gas Collection System in Retrofit Landfill Bioreactor Cells

3.2.2 Municipal Solid Waste Sampling

MSW samples were collected biennially (every two years) through discrete borings advanced into the landfill units. The sampling location protocol required dividing the cell into six sections and then dividing each section into approximately 3 m × 3 m (10 ft × 10 ft) grids and randomly choosing a square within the grid. This boring location protocol was used for assigning the sampling locations in the remaining sections. Within each unit, the same 3 m × 3 m (10 ft × 10 ft) grid was used for subsequent sampling events. Sampling at the edges of the cell was avoided. In addition, if drilling at a selected location could not be initiated (e.g., known location of asbestos placement) or if the boring could not be completed (e.g., an impenetrable object was encountered) at a selected location, a randomly selected square adjacent to the original location was selected.

The following protocol was used for MSW sampling during the study: (i) the surface elevation of the sampling location was established; (ii) a drill rig equipped with an approximately 0.9 m (3 ft) diameter bucket auger was used to drill into the solid waste mass; (iii) each location was sampled in approximately 3 m (10 ft) long vertical sections; (iv) a composite sample was obtained at each 3 m (10 ft) long depth interval at each boring location; (v) the initial 3 m (10 ft) of material at each location was generally discarded as it predominantly contained cover soil (or at least a disproportionate amount of soil); (vi) as the boring advanced, each 3 m (10 ft) long sample was extracted from the auger and the appearance of the waste was observed and recorded; and (vii) at least five composite samples were collected from each of six sampling locations in each sampling time period. As such, a minimum of 30 MSW samples were collected for each cell on a biennial basis. This sampling schedule is summarized in Table 3-5.

Temperature and ORP of the in-place MSW were measured by Type T-thermocouple probes connected to a PC-driven data collection system. The data communications system for the probes was designed to record the temperature and ORP for each probe once every 30 minutes. These data were used to construct a control chart for each probe. Probes installed in the Retrofit cells were mostly temporary, and as such were removed, inspected, reconnected, and replaced (as necessary).

Table 3-2 Leachate Sampling Parameters and Schedule

Parameter	Frequency	Method
Head on liner	Continuous	Pressure Transducer
Leachate production	Continuous	Flow Meter
COD	Monthly	SM 410.4(1)
BOD	Monthly	SM 405.1
Ammonia-nitrogen (NH3-N)	Monthly	SM 350.1
Ortho Phosphate / Total Phosphate	Monthly	SM 365.2 (c)
Nitrate-nitrogen (NO3-N)	Monthly	SM 300.1
Nitrite-nitrogen (NO2-N)	Monthly	SM 300.1
Total volatile fatty acids	Monthly	GC MS
Temperature	Monthly	Thermometer
TOC and DOC	Monthly	U.S. EPA 9060
pH	Monthly	U.S. EPA 9045
VOC	Quarterly	SW-846 8260(B)
SVOC	Quarterly	SW-846 8270(B)
TKN	Quarterly	
Total dissolved solids	Quarterly	SM 160.1(C)
Sulfate	Quarterly	SM 300.1
Chloride	Quarterly	SM 300.1
Potassium	Quarterly	
Conductance	Monthly	Electrode
Metals (As, Ba, Cd, Ca, Cu, Cr, Fe, Pb, Mg, Hg, K, Na, Se, Ag, Zn)	Quarterly	SW-846 6010

Notes: Standard Methods (APHA 1999).

Table 3-3 Volatile Organic Compounds Examined in Landfill Leachate

Chemical Compound Name	Chemical Compound Name	Chemical Compound Name
Ethylbenzene	Carbon Tetrachloride	1,1,1-Trichloroethane
Styrene	2-Hexanone	Bromomethane
cis-1,3-Dichloropropene	1,1,1,2-Tetrachloroethane	Chloromethane
trans-1,3-Dichloropropene	Acetone	Iodomethane
1,4-Dichlorobenzene	Chloroform	Dibromomethane
1,2-Dibromoethane (EDB)	Benzene	Bromochloromethane
Acrolein	1,1,2,2-Tetrachloroethane	Chloroethane
1,2-Dichloroethane	1,2-Dichlorobenzene	Vinyl chloride
Acrylonitrile	1,2-Dibromo-3-Chloropropane DBCP	Methylene chloride
Vinyl acetate	1,2,3-Trichloropropane	Carbon Disulfide
Methyl Isobutyl Ketone	Ethyl methacrylate	Bromoform
Toluene	Methyl Ethyl Ketone	Dichlorobromomethane
Chlorobenzene	1,1,2-Trichloroethane	1,1-Dichloroethane
trans-1,4-Dichloro-2-butene	Total Xylenes	1,1-Dichloroethene
2-Chloroethylvinyl ether	cis-1,2-Dichloroethene	Trichlorofluoromethane
Dibromochloromethane	Dichlorodifluoromethane	Trichloroethene
Tetrachloroethene	1,2-Dichloropropane	trans-1,2-Dichloroethene

Table 3-4 Semi Volatile Organic Compounds Examined in Landfill Leachate

Chemical Compound Name	**Chemical Compound Name**	**Chemical Compound Name**
4-Nitroaniline	Thionazin	Pentachlorophenol
4-Nitrophenol	Methyl parathion	2,4,6-Trichlorophenol
Benzyl alcohol	Phorate	2-Nitroaniline
N-Nitrosopiperidine	Disulfoton	2-Nitrophenol
4-Bromophenyl phenyl ether	Isodrin	2-sec-Butyl-4,6-dinitrophenol
2,4-Dimethylphenol	Benzo(a)pyrene	Naphthalene
N-Nitrosomethylethylamine	2,4-Dinitrophenol	2-Methylnaphthalene
Cresol, p-	Chlorobenzilate	2-Chloronaphthalene
1,4-Dichlorobenzene	Famphur	2-Naphthylamine
4-Chloroaniline	Dibenzo(a,h)anthracene	Methapyrilene
p-Phenylenediamine	2-Acetylaminofluorene	3,3'-Dichlorobenzidine
Cresol, m-	Cresol, 4,6-Dinitro-O-	4-Aminobiphenyl
2,2'-Oxybis(1-Chloropropane)	1,3-Dichlorobenzene	N-Nitrosodi-n-butylamine
Phenol	N-Nitrosodiethylamine	N-Nitrosopyrrolidine
Bis(2-chloroethyl) ether	Parathion	Safrole
Bis(2-chloroethoxy) methane	3-Methylcholanthrene	Cresol, o-
Bis(2-ethylhexyl) phthalate	Benzo(a)anthracene	1,2-Dichlorobenzene
Di-n-octyl phthalate	7,12-Dimethylbenz(a)anthracene	o-Toluidine
Hexachlorobenzene	2,3,4,6-Tetrachlorophenol	2-Chlorophenol
3,3'-Dimethylbenzidine	Cresol, p-Chloro-m-	1,2,4,5-Tetrachlorobenzene
Anthracene	p-Dimethylaminoazobenzene	2,4,5-Trichlorophenol
Isosafrole	Dimethoate	Acetophenone
1,2,4-Trichlorobenzene	2,6-Dinitrotoluene	Nitrobenzene
2,4-Dichlorophenol	Pentachlorobenzene	3-Nitroaniline
2,4-Dinitrotoluene	Phenacetin	sym-Trinitrobenzene
Diphenylamine	Ethyl methane sulfonate	5-Nitro-o-toluidine
1,4-Dioxane	N-Nitrosodimethylamine	m-Dinitrobenzene
0,0,0-Triethylphosphorothioate	N-Nitroso-Di-n-propylamine	N-nitrosodiphenylamine
Pyrene	Methyl methanesulfonate	Fluorene
1,4-Naphthoquinone	Hexachloroethane	2,6-Dichlorophenol
Dimethyl phthalate	4-Chlorophenyl phenyl ether	Hexachlorobutadiene
Dibenzofuran	Hexachlorocyclopentadiene	Benzo(k)fluoranthene
1-Naphthylamine	Isophorone	Acenaphthylene
Kepone	Pentachloronitrobenzene	Chrysene
Hexachloropropene	Acenaphthene	Diallate
Benzo(ghi)perylene	Diethyl phthalate	Pronamide
Indeno(1,2,3-cd)pyrene	Di-n-butyl phthalate	Butyl benzyl phthalate
Benzo(b)fluoranthene	Phenanthrene	Fluoranthene

Table 3-5 Municipal Solid Waste Sampling Schedule

Parameter	Collection Frequency
ORP	Daily
Temperature	Daily
Solid waste settlement	Quarterly
Waste moisture	Biennially
pH	Biennially
Cellulose and lignin content	Biennially
Organic solids	Biennially
BMP	Biennially

3.2.2.1 Analytical Methods for Solids Analysis

The procedures that were used to process solid samples have been fully described in the QAPP presented in the First Interim Report, and are summarized here. Samples were excavated as described above. After excavation, a composite sample was mixed and then grab samples were placed in a 19 liter (5 gallon) bucket for shipment for analysis. Upon receipt, samples were stored at 4 °C (40 °F) to preclude additional biodegradation. Samples were initially shredded to a width of about 20 mm (0.8 in.) and a length of 50 to 100 mm (2 to 4 in.). After shredding, samples were again stored at 4 °C (40 °F) until they could be dried. Approximately 1 to 2 kg (2.2 to 4.4 lb) of each sample was dried for analysis of moisture content and solids composition. After drying, samples were ground using a Wiley Mill to pass a 1 mm (0.04 in.) screen and then re-dried prior to analysis. When pieces of metals and/or textiles were encountered in the sample, the materials were cut into small pieces prior to grinding. Alternately, small pieces of metal were substituted for larger pieces to maintain a similar metal concentration.

The concentrations of cellulose and hemicellulose were analyzed by subjecting a sample to a two-stage acid hydrolysis (Petterson and Schwandt 1991). After washing a sample with a 2:1 mixture of toluene and 95 percent ethanol to remove lipids, a solid sample was subjected to a 72 percent H_2SO_4 primary hydrolysis followed by a 28 fold dilution for the secondary hydrolysis. These hydrolyse convert the cellulose and hemicellulose to their component simple sugars. Cellulose is a polymer of glucose, while hemicellulose is a polymer of arabinose, galactose, mannose, and xylose. The solubilized sugars were analyzed by using a high performance liquid chromatograph equipped with a pulsed amperometric detector. Sugars were separated with a Carbo-Pac PA1 column manufactured by Dionex Corp., Sunnyvale, CA. The mobile phase was 50 percent NaOH with 40.4 mL of 1.5 M sodium acetate added per liter of 50 percent NaOH eluent. Water was circulated around the column to dampen temperature variations. Fucose was used as an internal standard to correct for losses during the hydrolysis procedure (Davis 1998).

A new high performance liquid chromatograph system was used for the samples analyzed in 2005. The same procedure was used although the detector was a pulsed electrochemical detector. In addition, it was no longer necessary to circulate water to maintain column temperature with the new liquid chromatograph. The solids that remained after the acid hydrolysis consisted of organic and inorganic materials. These solids were then combusted for 2 hrs at 550 °C (1,022 °F) with the weight loss on combustion considered lignin (Petterson and Schwandt 1991). In all likelihood, this procedure slightly over predicted the amount of lignin as the material “counted” as lignin also included some plastic, rubber, and leather that were not removed during the acid hydrolyses.

Organic solids concentrations were determined by the weight loss of the dried samples after combustion for 2 hrs at 550° C (1,022 °F). All solids analyses were performed in duplicate and average data were utilized for the regression analyses described below. Samples were reanalyzed in all cases where the relative percent deviation (RPD), as defined in equation 3-2, exceeded 20 percent.

$$\text{RPD} = \frac{\text{standard deviation}}{\text{mean}} \times 100 \qquad \text{Equation 3-2}$$

3.2.2.2 Biochemical Methane Potential

Samples were placed in 160 mL capacity serum bottles after which a biochemical methane potential (BMP) medium was added (Wang et al. 1994). Bottles were then inoculated using 15 mL of a methanogenic consortium that were maintained on freshly ground MSW. Serum bottles were filled and maintained under anaerobic conditions with an 80/20 mixture of N_2 and CO_2 gas and incubated at 37 °C (99 °F). After 60 days of incubation, the majority of the gas volume was measured by using a 60 mL capacity plastic syringe. A 5 mL capacity wetted glass syringe was then used to measure the remaining overpressure. BMP results were corrected for CH_4 production attributable to the inoculum and to standard temperature and pressure. The concentration of CH_4 was measured by using a gas chromatograph equipped with a thermal conductivity detector and a CTR1 column manufactured by Alltech, Deerfield, IL. BMP assays were conducted in triplicate and five replicates were conducted to measure CH_4 production associated with the inoculum. If the RPD exceeded 20 percent, then samples were reanalyzed unless two replicates were consistent, in which case the outlier was discarded.

3.2.2.3 Use of Cellulose Plus Hemicellulose to Lignin Ratios

Historically, daily and intermediate covers were applied to each landfill cell and the amount of soil was estimated to range from 10 to 25 percent of the waste volume. Thus, there is the potential to include soil in refuse samples that are excavated from landfills. The soil component of the sample will dilute the cellulose, hemicellulose, and lignin concentrations in the sample. The most effective way to eliminate the effect of soil dilution is to analyze data based on the cellulose plus hemicellulose to lignin (CH:L) ratio rather than the concentration of either the cellulose or hemicellulose. While advantageous from the perspective of eliminating the influence of the soil, this method has the disadvantage that the initial CH:L ratio of the buried refuse is often unknown or only known within a range. The variation in the CH:L ratio for fresh refuse was presented in Table 2-5. This ratio may be different when all of the different waste streams entering a landfill are considered.

3.2.4 Landfill Settlement

Settlement of the landfill was monitored on a quarterly basis as a secondary indication of decomposition and stability using a GPS measurement of surface elevation. GPS surveying was performed using a Trimble Model 4800 for the settlement plates within each cell using the following protocol: (i) every sampling event was initialized from a known point that was controlled at ± 5 cm (2 in.) for horizontal and vertical control (if sampling within a cell was interrupted, the system was reinitialized from the known point before sampling resumed); (ii) sampling was initiated if the root mean square reading from the system was ≤ 10 cm (4 in.); and (iii) the positional dilution of precision as measured on the device was ≤ 6 before the GPS system could be used. In addition, one of every 20 settlement plates measured by the GPS unit was randomly selected and re-tested. These results were compared to the limits established in the QAPP presented in the First Interim Report. If the three aforementioned conditions were met, the positional accuracy of the GPS readings was reported to be sufficient to meet the analytical needs of the study. A detailed landfill settlement analysis is not included in Chapter 4, as waste filling occurred continuously in the Control cells until 2004, and waste filling occurred in the As-Built cells until 2005. Since waste filling occurred in these cells throughout the monitoring period, an assessment of total settlement and a correlation between waste decomposition and settlement could not be made. Monitoring of the settlement points will continue at the site and a correlation between waste settlement and waste degradation will be investigated as part of the Final Report.

3.2.5 Landfill Gas Sampling

3.2.5.1 Gas Collection System Sampling

The LFG sampling schedule is presented in Table 3-6. Primary LFG constituents (i.e., CH_4, CO_2 and O_2) were measured weekly, whereas trace gases (i.e., NMOCs, including individual HAPs) were measured quarterly. Surface emissions monitoring of CH_4 was conducted quarterly, if required. Table 3-7 indicates the specific HAPs (which are a subset of NMOCs) that were analyzed for in each sample. Similar to the leachate sampling protocol, LFG sampling occurred at one point per cell. The LFG extraction wells are located systematically across the cell, approximately equidistant from each other, to provide relatively uniform extraction coverage.

Table 3-6 LFG Sampling Schedule

Parameter	Collection Frequency
LFG flow	Weekly
LFG percent composition (CH_4, CO_2, O_2,)	Weekly
HAPs	Quarterly
Surface emission monitoring (CH_4)	Quarterly

LFG analysis was also performed for CH_4, CO_2, and O_2 using a CES Landtec GEM 2000 as outlined in the QAPP. This instrument is a portable field gas analyzer and uses a self-compensating infrared detector. After calibration, the instrument was connected to a gas sampling port on the selected gas header using flexible plastic tubing. Gas was drawn into the instrument by an internal pump. Results are date and time stamped and logged by the instrument. Gas standards for CH_4, CO_2 and O_2 were also analyzed twice daily on the day of sampling to evaluate accuracy objectives as outlined in the QAPP. Concentration readings for CO_2 and CH_4 were to be within 15 percent of the actual concentration or of the sample duplicate; the tolerance for O_2, was to be ± 30 percent. LFG analyses were made by electronically logging three consecutive measurements at a frequency of one measurement per minute of LFG composition and flow. Flow rate, differential pressure, static pressure, and temperature were recorded on the field instrument at each sample location (i.e., well, lateral, header, and flare). The mean value for each of these measurements was recorded and selected as the reported value for each parameter of interest.

LFG samples were also collected for laboratory analysis of CH_4, CO_2, N_2 and O_2 by U.S. EPA Method 3C, NMOCs were sampled and analyzed by U.S. EPA Method 25C, and HAPs were analyzed as identified in U.S. EPA Method TO-14. For the gas samples obtained for external laboratory analysis, samples were collected in 6 liter capacity SUMMA® passivated stainless steel canisters.

Table 3-7 HAPs Analyzed in Quarterly LFG Sampling

Chemical Compound	Chemical Compound	Chemical Compound
Dichlorodifluoromethane	Toluene	Vinyl acetate
Chloromethane	trans-1,3-Dichloropropene	cis-1,2-Dichloroethene
1,2-Dichloro-1,1,2,2-tetrafluoroethane	1,1,2-Trichloroethane	2-Butanone (MEK)
Vinyl chloride	Tetrachloroethene	Chloroform
Bromomethane	2-Hexanone	1,1,1-Trichloroethane
Chloroethane	Dibromochloromethane	Carbon tetrachloride
Trichlorofluoromethane	1,2-Dibromoethane (EDB)	Benzene
1,1-Dichloroethene	Chlorobenzene	1,2-Dichloroethane
Carbon disulfide	Ethylbenzene	Trichloroethene
1,1,2-Trichloro-1,2,2-trifluoroethane	Xylenes (total)	1,2-Dichloropropane
Acetone	Styrene	Bromodichloromethane
Methylene chloride	Bromoform	1,3,5-Trimethylbenzene
trans-1,2-Dichloroethene	1,1,2,2-Tetrachloroethane	1,2,4-Trimethylbenzene
1,1-Dichloroethane	Benzyl chloride	1,3-Dichlorobenzene
1,2,4-Trichlorobenzene	4-Ethyltoluene	1,4-Dichlorobenzene
Hexachlorobutadiene	4-Methyl-2-pentanone (MIBK)	1,2-Dichlorobenzene
cis-1,3-Dichloropropene		

3.3 Data Processing and Statistical Analysis

3.3.1 Sample Dating and Statistical Analysis

The primary goal of the study at the OLLB was to evaluate the extent to which the operation of a landfill as a bioreactor accelerated refuse decomposition. The CH:L will be used as a metric to compare samples excavated from different landfill cells. However, waste age must also be considered as refuse decomposes over time, resulting in a change in this ratio (Barlaz 2006). Thus, six year old refuse from a Control cell may (or may not) be more decomposed than six month old refuse from a bioreactor landfill cell.

To evaluate the effect of decomposition over time, it was necessary to establish the age of the solid waste at the time of sample collection. The age of the waste represented by each sample was estimated from site survey data that were specific to the location of each boring. The survey data provided historical waste placement information that allowed an estimate of the age of each sampling interval for each boring. Typically, survey data were available to document the date of waste filling through the entire depth of the landfill. In some cases, it was not possible to estimate the age of waste from a specific boring. In such cases, that data were excluded from the analyses presented in this section. Over the entire data set, 3.4 percent of the samples were excluded because of a lack of information regarding waste age.

To evaluate reproducibility between cells, a given characteristic of the refuse (e.g., moisture content) was initially compared between cells by using a t-test in Microsoft Excel®. All of these analyses were conducted using a two-sided t-test, assuming unequal variance in the data. In general, data sets were only considered significantly different if the results of the t-test indicate a probability (p-value) of less than 0.05, meaning that there is a 95% probability that a difference is relevant in consideration of sample variability.

To evaluate decomposition as a function of time, the CH:L, BMP and organic solids data for a specific cell were plotted as a function of waste age, and a linear regression was conducted. The slope of the best fit line from the linear regression was then evaluated to determine whether the slope was significantly different from zero by calculating the 95 percent confidence intervals for each slope using the regression analysis tool in Microsoft Excel. If the 95 percent confidence interval included a slope of zero, then the slope was judged to be statistically similar to zero. A slope of zero means that there was not a significant decrease in the measured parameter (e.g., BMP) with respect to waste age. Slopes for all linear regressions and the corresponding 95 percent confidence intervals are presented in Section 4.1. The same procedure has been used in previous research (Barlaz et al. 2004).

Diagnostic plots were analyzed to ensure linear regression model assumptions were met and to investigate the influence of individual points upon the fit. A plot of residuals versus fitted values was used to assess the assumption of constant error variance. A normal quantile-quantile plot was used to assess the assumption that errors were distributed normally. A residuals-versus-leverage plot was used to investigate the influence of individual points on the regression fit.

As illustrated by Equations 2-2 and 2-3, the biodegradation of cellulose and hemicellulose is linked to CH_4 production. As described in Section 4.3, the predictive CH_4 generation model is exponential. Thus, the CH:L and BMP are more likely to decrease exponentially as the remaining substrate (i.e., cellulose and hemicellulose) becomes less bioavailable. In this respect, a first order decay model may be a more appropriate mathematical representation of solids decomposition as a function of waste age. A linear regression model was used here only as a method to rapidly assess a large amount of data and to assess statistically whether the calculated slopes were significantly less than zero. The calculated model is not intended for use in a predictive mode based on the analyses presented in this section. It should also be noted that a linear model is not ideal when working with a ratio (CH:L). However, of the three solids decomposition parameters evaluated (CH:L, BMP, and organic solids), CH:L is the only one that eliminates the influence of soil dilution. Thus, it was judged important to use this ratio in a linear regression.

A multiple linear regression analysis was also conducted. Five variables were considered (waste age, sampling date, sample elevation, moisture content, and temperature). First, the correlation between the five variables was investigated. Next, multiple parameters were evaluated, including both individual parameters (e.g., moisture content), and parameter interactions (e.g., sampling date × elevation). Best-fit models were developed using R, a statistical modeling software (www.r-project.org), and the results were inspected qualitatively using both the adjusted R^2 and the significance of the parameter modeled. The adjusted R^2 is comparable to R^2 for the linear regression analysis in that it is corrected for the used multiple parameters.

3.3.2 Moisture Balance Calculations

As a part of this study a moisture balance was conducted to provide confirmation of the "apparent" or "anticipated" increase in the bulk moisture content of the waste. Waste moisture content was also directly measured during the biennial solid waste sampling events. An evaluation was made to compare the calculations to the measured values. The Control and Retrofit cells were each considered as a single unit due to the lack of any hydraulic separation between their subcells. As-Built cells A and B, however, were considered as individual units because of the clay barrier separating them. The moisture balance calculations were performed for the all the cells between March 2002 and December 2005. Parameters used in preparing the moisture balance included: (i)volumes of recirculated leachate; (ii) supplemental liquid addition; (iii) estimated infiltration; (iv) estimated surface run-on; and (v) measured leachate generation. Moisture generated as a result of biological or chemical interactions within the landfill cells was neglected as a source of additional liquids in the moisture balance calculations. Moisture leaving the landfill through the gas collection system as condensate was also not included in the moisture balance calculations. These two sources were not expected to significantly influence the results of the analysis (less than approximately 1500 cubic meters per cell) expressed in %.

March 2002 was chosen as the start date because solid waste samples were collected from each cell during that month and analyzed for (among other parameters) moisture content. Since the sampling was conducted prior to liquids addition in the bioreactor cells, the mean moisture content from the March 2002 solid samples was used as the initial moisture content in the moisture balance calculations. Thus, the estimated initial moisture content (on a wet weight basis) was 32.5 percent for the Control cells, 37 percent for the Retrofit cells, 42 percent for As-Built cell A, and 43 percent for As-Built cell B. Typical moisture content on a wet weight basis (i.e., mass of water divided by mass of wet waste) of incoming waste can range from 15 to 40 percent (Tchobanoglous 1998). It is acknowledged that these moisture content values are on the high end of the "typical" range of waste moisture content reported by Tchobanoglous (1998). Given the relatively wet climate of Louisville and the fact that the data utilized are from a single sampling event, the actual moisture content of as-received waste may be less than what was measured in the March 2002 samples. However, using these data provided the best starting point for estimating an initial moisture content amount for use in the moisture balance calculations.

With regard to the parameters used in performing the moisture balance, the volume of recirculated leachate, the volume of supplemental liquids added, and the volume of the generated leachate were recorded daily. Precipitation at the site was recorded daily at an on-site weather station. To account for infiltration, runoff and evapotranspiration, parameters were estimated using the Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al. 1994). The type of cover material, thickness of the cover material, slope of the waste surface, and slope length were selected as input parameters to the HELP model. Only the surface of each landfill cell was modeled in HELP to calculate runoff, evapotranspiration, and infiltration. Details regarding selection of the specific input parameters were obtained using available survey maps and by communication with the OLRDF's site manager. For the Control cells, Retrofit cells, and sloped surfaces of the As-Built cells, the cover material was assumed to be clay with a hydraulic conductivity of 1×10^{-6} cm/s (4×10^{-7} in/s). The thickness of the clay cover was assumed to be approximately 1 m (3 ft). The flat areas of the As-Built cells consisted of a cover material made of an approximately 0.3 m (1 ft) thick layer of compost with a hydraulic conductivity of about 4×10^{-2} cm/s. The compost cover material was replaced by a 1 m (3 ft) thick layer of clay in August 2004. The slope of the landfill units was 4 horizontal to 1 vertical (4H:1V) and the length of the slope was assumed to be 76 m (250 ft). Additional details on the moisture balance parameters for the different units are presented in Table 3-8. The topography of the landfill units and the ratio of the sloped versus flat areas of the landfill units was estimated using contour intervals from the survey maps that were available from March 2002 to December 2005. These estimates are presented in Table 3-9 (As-Built cells) and Table 3-10 (Retrofit and Control cells). It is noted that because the day-to-day details of waste filling and covering were not available, the inputs to the HELP model are best estimates, and the results should be treated as such.

Run-on was the only parameter that was not recorded or calculated directly; rather, it was estimated based on runoff values output by the HELP model and the geometry of each cell. Run-on from Unit 7.2 (located to the north of As-Built cell A) to As-Built cell A, run-on from Control cell A to Control cell B, and run-on from the Control cell to As-Built cell B was included in the estimated/calculated infiltration volumes. Run-on percentage was estimated using the parameters presented in Table 3-8. Run-on from unit 7.2 to Control cell A was assumed to be 25 percent of rainfall. This was based on an average value of runoff in the sloped and flat surfaces of unit 7.2. It is noted that prior to late 2003, most of the run-on volume did not infiltrate to the As-Built cells, but rather was channeled directly to the LCS, as presented in survey maps and reported by WM. This was due to the inclusion of a "column" of rubber tire chips that were placed between: (i) unit 7.2 and As-Built cell A; (ii) As-Built cell A and As-Built cell B; and (iii) As-Built cell B and Control cell B. The channeling was assumed to cease after the first quarter of 2004 when tire chips were no longer placed at the edges of the cells.

Table 3-8 Moisture Balance Parameters

Parameter	Control & Retrofit Sloped Area	Control & Retrofit Flat Area	As-Built Sloped Area	As-Built Flat Area
Runoff (percent)	51	49	51	3.5
Evapotranspiration (percent)	47	48.5	47	60
Infiltration (percent)	2	2.5	2	36

Table 3-9 Area Distribution of As-Built cells

Date\Units	As-Built cell A Sloped Area, m^2 (acres)	As-Built cell A Flat Area, m^2 (acres)	As-Built cell B Sloped Area, m^2 (acres)	As-Built cell B Flat Area, m^2 (acres)
Mar 02-Oct 02	12141(3.0)	39659 (9.8)	0	36017 (8.9)
Nov 02-Feb 03	10117 (2.5)	18211 (4.5)	3237 (0.8)	38850 (9.6)
Mar 03- May 03	12950 (3.2)	16187 (4.0)	8094 (2.0)	32375 (8.0)
Jun 03-Nov 03	12141 (3.0)	18211 (4.5)	14164 (3.5)	32375 (8.0)
Nov 03-Oct 04	12141 (3.0)	18211 (4.5)	14164 (3.5)	46539 (11.5)
Nov 04 – Apr 05	12141 (3.0)	18211 (4.5)	40469 (10)	22662 (5.6)
June 05-Dec 05	566 (1.4)	13759 (3.4)	40469 (10)	22662 (5.6)

Table 3-10 Area Distribution of Retrofit and Control Units

Date\Units	Retrofit Sloped Area, m^2 (acres)	Retrofit Flat Area, m^2 (acres)	Control Sloped Area, m^2 (acres)	Control Flat Area, m^2 (acres)
Mar 02-Dec 05	99553 (24.6)	19425 (4.8)	33994 (8.4)	0

3.3.3 Statistical Analysis of Leachate Parameters

Multiple linear regressions were utilized to quantify trends in the leachate parameters of interest. Two explanatory variables were used in the regression fits, sampling date and a phase-shifted sine function of the sampling date (to capture a possible seasonal component). The sine variable was phase-shifted to have a maximum on September 1st and minimum on March 1st. For the regression fits, the parameter Sampling Date is the number of days between the sampling date and 1/1/1970.

While not presented, several diagnostic plots were analyzed to ensure linear regression model assumptions were met and to investigate the influence of individual points upon the fit. A plot of residuals versus fitted values was used to assess the assumption of constant error variance. A normal quantile-quantile plot was used to assess the assumption that errors are distributed normally. Residual versus leverage plot was used to investigate the influence of individual points on the regression fit.

Chapter 4. Solid Waste and Moisture Content Analysis

A data validation report, which confirms that data presented herein were collected according to the specifications outlined in the QAPP in the First Interim Report and provides validation of data presented in this section, is included as Appendix A.

4.1 Solid Waste Analysis

The objective of Section 4.1 is to present and analyze data on the composition of solids excavated from the Control, As-Built, and Retrofit cells of the OLLB between 2000 and 2005. Major sampling events were conducted in 2000, 2002, 2003, and 2005. In addition, fresh waste entering the Control and As-Built cells was characterized in 2001 and 2004. The solids composition data from the OLLB are presented and discussed in Section 4.1.1. To the authors' knowledge, the data presented in this section represent the largest data set of refuse samples from a single site available to date.

4.1.1 Results

The primary focus of this section is to present and analyze data on the composition of the solids excavated from the Control, As-Built, and Retrofit areas. The discussion focuses on the following two questions:

1. Do the solids composition data support the assumption that replicate cells actually behaved as replicates? This applies to a comparison of results from replicate areas of the Retrofit, Control, and As-Built cells. Data from cells 5.1A and 5.1B are referred to as Retrofit cell A, and data from cells 5.2A and 5.2B are referred to as Retrofit cell B.
2. Do the solids composition data support the hypothesis that the operation of a landfill cell as a bioreactor accelerates the biodegradation of organic matter as described by equations 2-2 and 2-3. It is recognized that there are inherent differences in the Retrofit and As-Built landfill bioreactors. As such, some caution is warranted in analysis of the results.

The discussion in this section addresses these two questions from the perspective of the solids composition data only. Later in this report, the solids, gas, and leachate data are considered together to evaluate whether there is evidence that operation as a bioreactor landfill resulted in accelerated refuse decomposition.

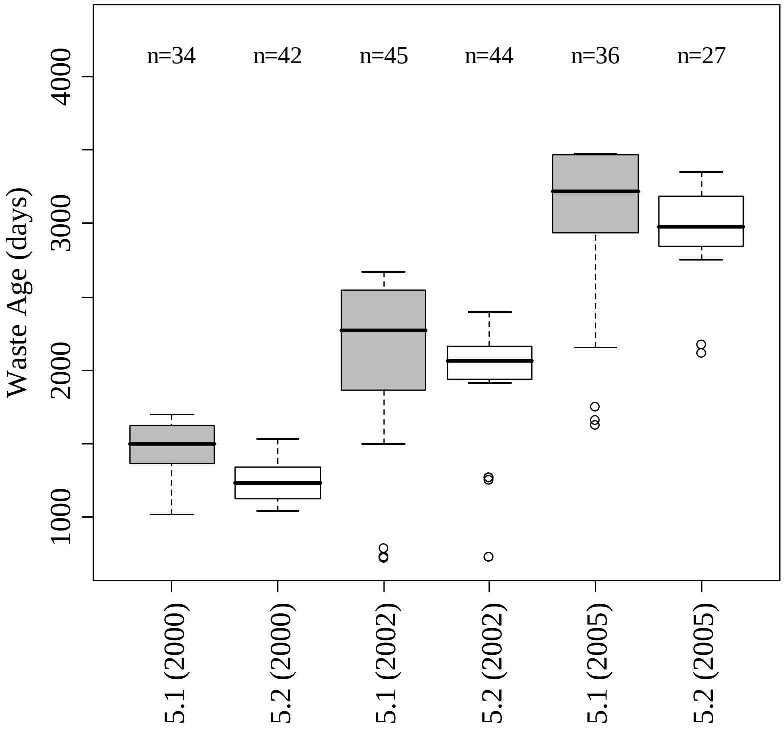
4.1.1.1 Solids Decomposition in the Retrofit cell

The first assessment of "data reproducibility" is to compare the calculated waste age from Retrofit cells A and B (i.e., 5.1 and 5.2). If there is a significant difference in the waste age between cells that cannot be explained by the cells' fill histories, it suggests that the procedure used to date the waste is not entirely appropriate. In comparing the intercell variability, the waste age in Retrofit cell A was older than that in Retrofit cell B by 222, 89 and 89 days in 2000, 2002 and 2005, respectively (Table 4-1). This difference was only significant ($p < 0.05$) in 2000 when the waste was youngest and small differences would be more significant. The actual difference may be important for waste less than five years old, but becomes less important over time. The waste age data are encouraging as they are reasonably consistent. This suggests that the solids decomposition data can be assessed with respect to the calculated waste age. Another way to assess differences in waste age between cells would be to evaluate the distribution of the sample age data as presented in Figure 4-1.

As described in Chapter 3, the Retrofit cells are reported to be composed of approximately 32 percent soil. While this will not affect the CH:L, it will reduce the BMP, which is expressed on a "per dry mass" basis. As presented in Table 4-1, there are significant differences between Retrofit cells A and B in 2005 for CH:L, BMP, and organic solids. The 2005 trends are consistent in that all three measures of solids decomposition suggest that the solids from Retrofit cell A are more decomposed relative to samples from Retrofit cell B. However, this observation is not consistent with the measured moisture contents, which are statistically similar between Retrofit cells A and B in 2005. The decomposition rate data, which are described below, do not support the hypothesis that the rate of decomposition is different between Retrofit cells A and B.

Table 4-1 Summary of Waste Composition Data for the Retrofit cell

Sampling Year	Subcell	Statistical Parameter	Waste Age at Time of Sampling (days)	Moisture (%)	CH:L	BMP (mL CH_4/dry gm)	Organic Solids (%)
2000	A (5.1)	average	1,470	34.7	1.17	31.3	37.3
		stnd. dev.	191	6.3	0.69	21.5	12.6
	B (5.2)	average	1,248	35.0	1.31	43.2	43.6
		stnd. dev.	135	6.0	0.88	34.9	15.8
	p-value		9.38E-08	0.87	0.44	0.087	0.063
2002	A (5.1)	average	2,077	37.7	1.20	25.9	33.1
		stnd. dev.	612	7.5	0.65	20.4	10.4
	B (5.2)	average	1,988	36.5	1.12	23.5	32.7
		stnd. dev.	342	7.7	0.46	15.4	10.6
	p-value		0.41	0.49	0.53	0.56	0.88
2005	A (5.1)	average	3,044	38.0	0.72	15.5	25.0
		stnd dev.	537	6.4	0.29	11.4	8.2
	B (5.2)	average	2,955	40.1	0.98	25.4	31.6
		stnd. dev.	296	6.52	0.55	20.4	13.0
	p-value		0.44	0.21	0.02	0.02	0.015



Note: The boxes encompass data between the 25th and 75th percentiles and the solid line in the box is the median. As illustrated, while the medians are close, there is more variability in the waste age in Retrofit cell A relative to Retrofit cell B in 2005. The whiskers represent the highest and lowest data points that are less than 1.5 × (75th percentile – 25th percentile) from the edges of the box, while the open circles represent data outside of this range.

Figure 4-1 Summary of Waste Age for Retrofit Cells A (5.1) and B (5.2)

A graphical depiction of trends in the relationship between waste age and CH:L, BMP, and organic solids are presented in several figures, included in Appendix B. Figure 4-2 depicts the combined Retrofit cell data, with no distinction between Retrofit cells A and B. This was done to utilize the largest data set possible, minimizing the confounding effects of other variables that may affect refuse decomposition. Additional analysis of the CH:L and BMP results in which the data were separated by area are presented in Appendix B. The statistics associated with the linear regression analysis are presented in Table 4-2.

For analysis purposes, regression modeling was chosen. There are several limitations to the use of linear regression models including whether a linear model is most appropriate, whether waste age is the most important independent variable, and whether multiple variables should be considered concurrently. As discussed in Chapter 3, a first order decay model may be a more appropriate mathematical representation of solids decomposition. However, as illustrated in Figure 4-2, the calculated exponential function is similar to the linear model for CH:L. Further assessment of exponential models is beyond the scope of this interim report, as the results suggest that additional data collection and analysis over the next several years is more critical.

When all of the CH:L data are combined for the Retrofit Unit, the slope of the regression is significantly less than zero at the 95% confidence level despite the high degree of scatter. This is also the case for the combined data for BMP and organic solids. A negative slope means that there is a statistically significant decrease in the value of a solids decomposition parameter with waste age. The BMP is a more sensitive measure of decomposition as it tracks changes in biodegradable solids only, while the organic solids includes both biodegradable organics (e.g., cellulose) and non-degradable organic solids (e.g., HDPE). With respect to the trends in decomposition as presented in Figure 4-2, the low correlation coefficients indicate that a single variable linear regression model does not completely characterize the measured trends. This is reasonable as there are many other variables affecting refuse decomposition. Multiple parameter regressions are discussed below.

When Retrofit cells A and B are analyzed separately (as presented in Table 4-2) for CH:L and BMP, the slopes are significantly less than zero for both measures in Retrofit cell A but only for BMP in Retrofit cell B. The results do not provide sufficient evidence to pursue further analyses of the data in which Retrofit cells A and B are treated differently as the larger data set associated with the combined area is more robust.

Many factors other than waste age are expected to be correlated with refuse decomposition including, for example, moisture content, pH, substrate quality and temperature. To evaluate whether moisture content alone was a better indicator of decomposition, the BMP and CH:L were plotted as a function of moisture content in Figure 4-3. As illustrated, moisture content was not a good predictor of the extent of decomposition. Two explanations for this result are that (i) the samples that contained elevated moisture were not wetter long enough for moisture to influence decomposition at the time of sampling; and (ii) other confounding variables precluded a clear trend. Ultimately, when all of the data from the Retrofit cells are considered, the increase in the average moisture content between 2000 and 2005, from 34.7% to 38.6%, was statistically significant ($p<0.05$) but not so dramatic as to be the only variable controlling either the CH:L or BMP. The use of multiple parameter regression models is discussed in Section 4.1.2.

4.1.1.2 Solids Decomposition in the Control cell

As presented in Table 4-3, there was not a significant difference in waste age between samples obtained from Control cells A and B in 2000, 2003, and 2005. Both the median waste age and the range were quite similar (Figure 4-4). The 225-day difference associated with the 2002 sampling, as well as the different ranges for Control cells A and B, was surprising and likely reflects some imprecision in the sample dating process (Figure 4-4). There were no significant differences in any of the waste monitoring parameters at any of the sampling periods, with the exception of the moisture content in 2005, when the average moisture content of samples from Control cell B was about four percent higher than samples from Control cell A (Figure 4-5). The moisture data for Control cell A in 2000 shows some particularly wet samples relative to Control cell B. The two wettest samples have moisture contents of 49.6 and 56.4%, respectively. However, the corresponding CH:L (2.84 and 1.49) and BMP (114.9 and 75.8 ml CH_4/dry gm) do not suggest that these two samples were well decomposed relative to the bulk of the samples (Figures presented in Appendix B). As the characteristics of Control cells A and B were quite similar, all subsequent analyses

Table 4-2 Slopes and Their 95% Confidence Intervals for Linear Regressions Between Waste Age and CH:L, BMP, and Organic Solids in the Retrofit, Control, and As-Built Cells

Cell	CH:L			BMP			Organic Solids		
	Lower Level	Slope	Upper Limit	Lower Level	Slope	Upper Limit	Lower Level	Slope	Upper Limit
Retrofit cells (A & B)	-3.3E-4	-2.3E-4	-1.E-4	-1.4E-2	-9.7E-2	-5.8E-3	-8.3E-3	-6.2E-3	-4.1E-3
Retrofit cell A	-3.9E-4	-2.6E-4	-1.2E-4	-1.3E-2	-8.8E-3	-4.5E-3	Not Analyzed		
Retrofit cell B	-3.4E-4	-1.5E-4	-3.0E-5	-1.7E-2	-9.7E-3	-2.5E-3			
Control cells	-2.6E-4	-9.5E-4	-7.0E-5	-1.8E-2	-1.1E-2	-4.5E-3	-5.3E-3	-2.1E-3	1.2E-3
As-Built cells (A & B)	-8.3E-4	-5.1E-4	-1.9E-4	-1.6E-2	-3.2E-2	9.2E-3	-1.4E-2	-8.1E-3	-2.4E-3
As-Built cell A	-1.2E-3	-7.2E-4	-2.5E-4	-3.5E-2	-1.9E-2	-2.6E-3	-1.7E-2	-1.0E-2	-3.3E-3
As-Built cell B	-7.5E-4	-3.0E-4	-1.5E-4	-2.3E-2	-4.3E-3	1.4E-3	-1.5E-2	-6.0E-4	3.3E-3

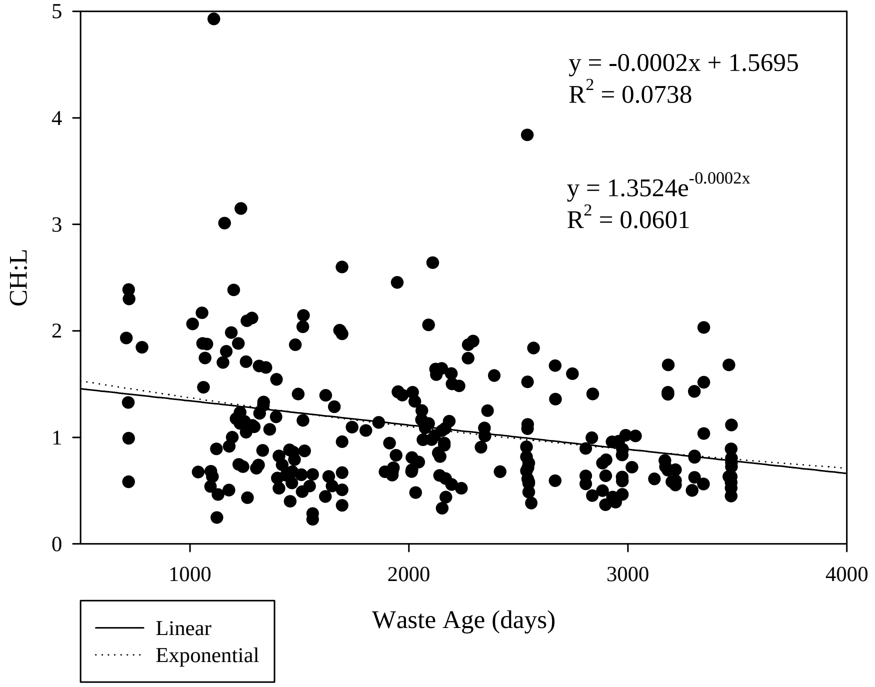


Figure 4-2 Relationship between CH:L and Waste Age in the Retrofit Cells

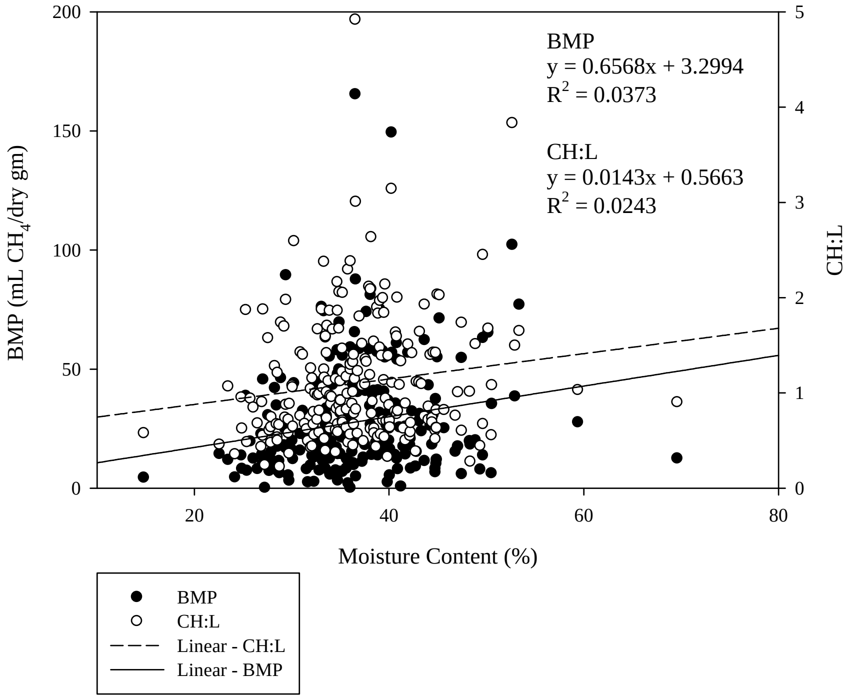


Figure 4-3 Relationship between Moisture Content and Solids Decomposition in the Retrofit Cells

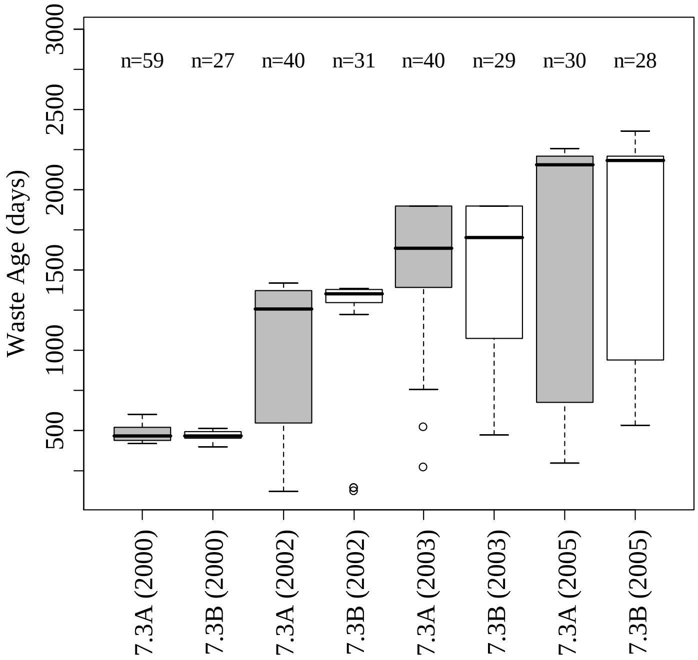


Figure 4-4 Waste Age Profile for the Control Cell A (7.3A) and Control Cell B (7.3B)

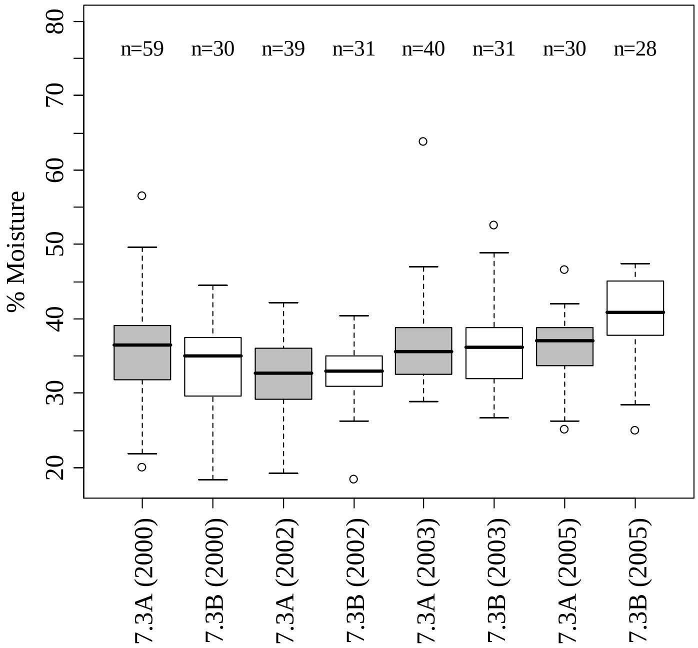


Figure 4-5 Moisture Content Profile for the Control cells at Each Sampling Time

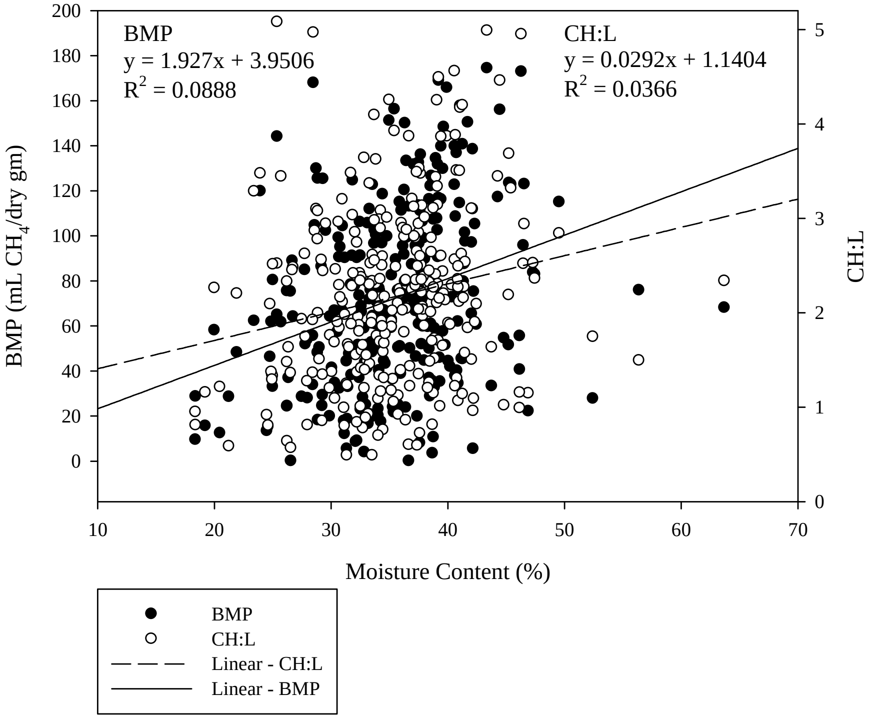


Figure 4-6 Relationship between Moisture Content and Solids Decomposition in the Control Cells

Table 4-3 Summary of Waste Composition Data for the Control cells and Assessment of Cell Replication

Sampling Year	Subcell	Statistical Parameter	Waste Age at Time of Sampling (days)	Moisture (%)	CH:L	BMP (mL CH_4 /dry gm)	Organic Solids (%)
2000	A	average	479	35.3	2.63	102.3	67.19
		stnd. dev.	50	6.8	0.93	37.5	16.35
	B	average	470	33.9	2.52	96.93	63.54
		stnd. dev.	30	6.15	1.10	38.15	16.84
	p-value		0.44	0.33	0.63	0.53	0.33
2002	A	average	1,000	32.4	1.34	34.4	41.7
		stnd. dev.	509	5.3	0.58	24.0	11.6
	B	average	1,225	32.6	1.42	37.8	46.0
		stnd. dev.	366	4.6	0.45	22.2	15.0
	p-value		0.042	0.84	0.50	0.55	0.18
2003	A	average	1,526	36.4	2.05	59.54	44.7
		stnd. dev.	422	6.0	0.69	29.58	12.4
	B	average	1,534	36.2	2.23	68.4	49.7
		stnd. dev.	463	6.0	0.65	25.8	13.8
	p-value		0.94	0.91	0.18	0.19	0.11
2005	A	average	1,657	36.0	2.68	88.6	71.2
		stnd. dev.	750	4.9	0.88	30.2	12.1
	B	average	1,655	40.1	2.52	82.5	73.0
		stnd. dev.	730	5.6	0.86	30.1	11.9
	p-value		0.99	0.01	0.47	0.45	0.57

of trends presented in this section are based on the combined data set (i.e., all of the data from the Control cells were combined to form a single data set).

The relationship between waste age and CH:L, BMP, and organic solids are presented in Appendix B, and the statistics associated with the linear regression analyses presented in these figures are presented in Table 4-2. The slopes of the regressions are only significantly less than zero at the 95% confidence level for the BMP, but not for the CH:L and organic solids. The limitations to the linear regression model that were described in the previous section apply to the solids data in the Control cells as well. As was the case for the Retrofit cells, moisture content was not a better predictor of waste composition than was waste age (Figure 4-7). The major purpose of the Control cells was to compare trends to the Retrofit and As-Built landfill bioreactor cells. Further discussion of these results are presented later in this section.

4.1.1.3 Solids Decomposition in the As-Built cells

A comparison of the waste age, moisture content, CH:L, BMP, and organic solids for As-Built cells A and B is presented in Table 4-4. In contrast to the Control area, there were several significant differences between As-Built cells A and B. With reference to Table 4-4, any comparison that exhibits a p-value of < 0.05 is considered to represent significantly different data sets. Thus, the waste age was consistently different and all measures of solids decomposition were different in 2003 and 2005. As described in Section 3.1.2.2, As-Built cell A received approximately five times more air than As-Built cell B. Given all of the differences, the data for As-Built cells A and B will be analyzed separately throughout this section.

In 2001 (and early 2002) and 2004, samples were only collected to characterize the fresh refuse added to each cell. As such, the samples sets were small (n=6) and trends with respect to sample date should not be inferred. These samples, however, were used to calculate L_o (methane generation potential of the waste (m^3 CH_4/Mg waste)) for gas generation model as is presented in Chapter 5. There was a significant difference in the moisture content in 2004 between the refuse added to As-Built cells A and B. Although both sets of samples were collected in May, 2004, their age is different and presumably more moisture was added to As-Built cell B over the 76-day residence time of these samples in the landfill.

The waste age increased in As-Built cell A between 2003 and 2005, whereas the average waste age was statistically similar between 2003 and 2005 in As-Built cell B. This was consistent with the addition of fresh waste to As-Built cell B between 2003 and 2005. A comparison of the waste age profiles for As-Built cells A and B is presented in Figure 4-7.

Trends in the relationship between waste age and CH:L, BMP, and organic solids are presented in Appendix B, and the statistics associated with the linear regression analysis for these figures are presented in Table 4-2. For As-Built cell B, the linear regression slopes were not significantly different from zero for any of the monitoring parameters (i.e., CH:L, BMP, and organic solids). As the calculated average waste age in As-Built cell B was only 545 days, thus a clear trend was not apparent. This is a very short time interval over which to observe any refuse decomposition.

For As-Built cell A, the slopes of all measures of decomposition, CH:L, BMP and organic solids were significantly less than zero (Table 4-2) which indicates that decreases in CH:L, BMP and organic solids with waste age were all statistically significant even though the average waste age was relatively young (730 days). The steeper slopes for the solids data for As-Built cell A relative to As-Built cell B were consistent with the fact that As-Built cell A received more air. The presence of air would have stimulated aerobic decomposition which is faster than anaerobic decomposition. Thus, the data suggest that the additional air added to As-Built cell A accelerated decomposition. As was the case for the Retrofit and Control cells, the moisture content was not a useful predictor of waste decomposition (Figures 4-8 and 4-9). This is not to suggest that moisture content is not a significant variable, but rather that the relatively young waste age coupled with other confounding variables mask a simple statistical relationship. As for the other test areas, these results suggest that additional monitoring in the coming years is warranted to be able to assess results and trends over a longer time period.

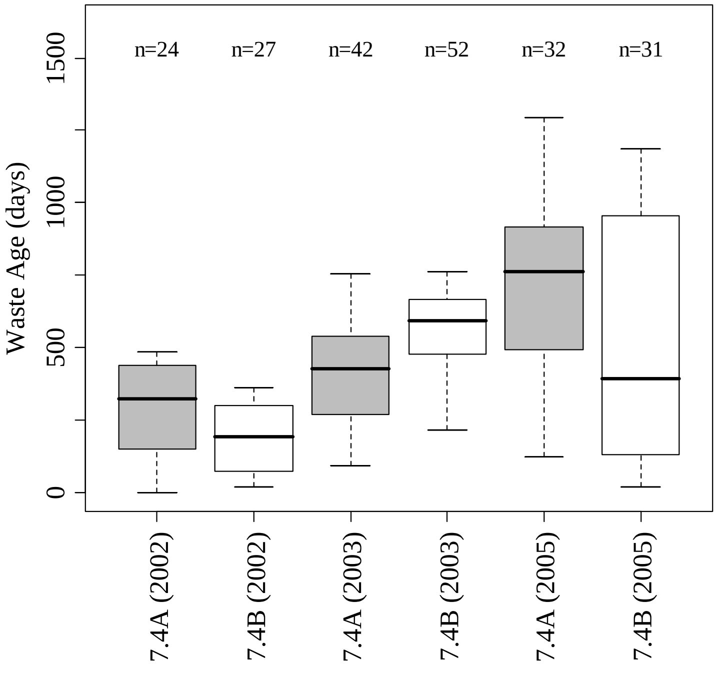


Figure 4-7 Waste Age Profile for As-Built Cells A and B

4.1.2 *Multiple Linear Regression Models*

Linear regression analyses using either waste age or moisture content as the independent variable indicated that neither of these parameters was able to explain the observed variation in CH:L, BMP or organic solids. This is reflected in the correlation coefficients presented with each linear regression. These coefficients were typically below 0.1 and never exceeded 0.13. In conducting a methodical search of potential single parameter relationships using moisture content, waste age, sampling date, sample elevation, and temperature, it was found that all variables except temperature were about the same in their ability, or inability in this case, to explain the observed trends in CH:L, BMP or organic solids. As a result, multiple linear regression analyses were conducted in an attempt to better explain the observed variation in solids decomposition monitoring parameters.

Subsequent work with temperature as a third variable did not improve the two variable (age, moisture) models, while the use of elevation offered slight improvements. Specifically, when elevation was used as the third variable for the same twenty four models, six had an adjusted R2 below 0.1, twelve had an adjusted R2 of 0.1 to 0.2 and six had an adjusted R2 of 0.27 to 0.50. Finally, work was conducted to explore models that included a sample date and an elevation term. The logic for this interaction was that it might account for waste settlement. While this model did offer an improved adjusted R2, the physical meaning of this term is not clear and the extent of settlement would actually reflect decomposition of waste under the sample, and not the sample itselfs. Thus, no further discussion of this model is presented.

The best multiple linear regression model was determined to be:

Decomposition Parameter = f (Moisture Percent + Waste Age + Elevation) Equation 4-1

In summary, the use of multiple linear regression analysis validates the significance of moisture content as a parameter that controls waste decomposition. However, given the number of other factors that affect decomposition, even a multiple parameter model could not account for most of the variability in the solids decomposition parameters.

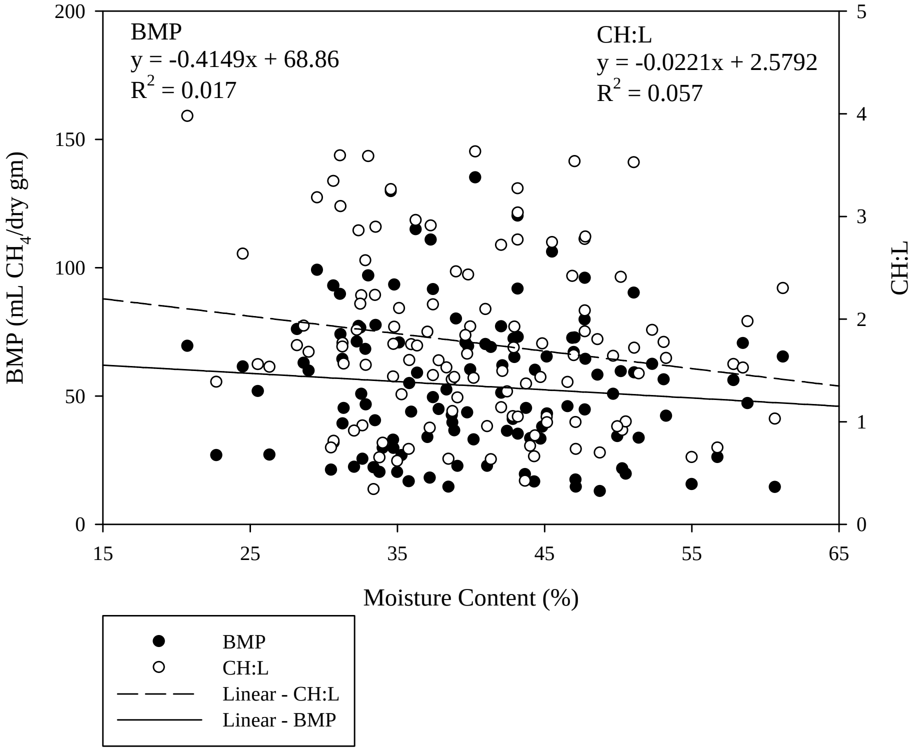


Figure 4-8 Relationship between Moisture Content and Solids Decomposition in As-Built Cell A

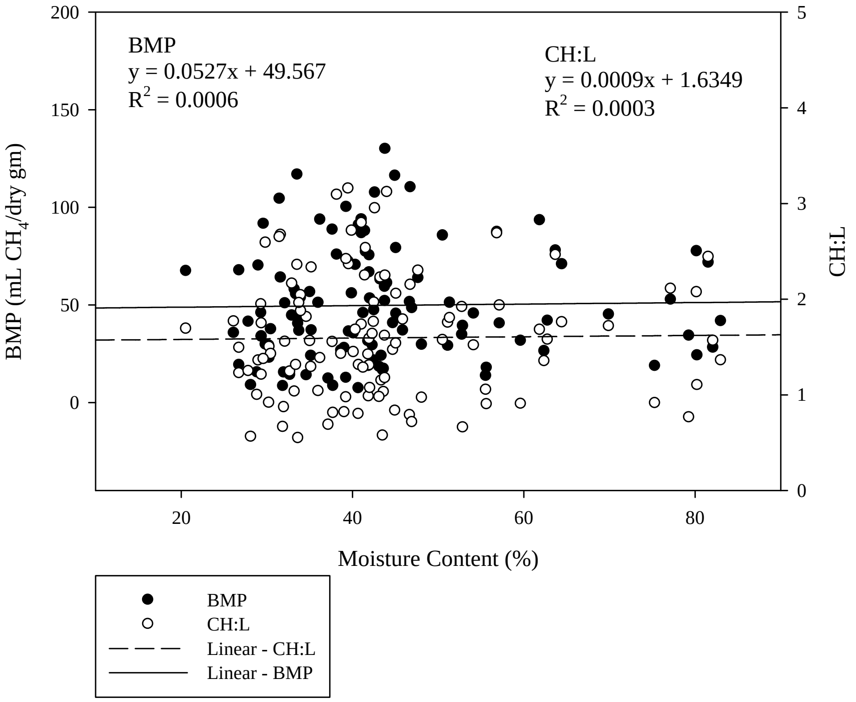


Figure 4-9 Relationship between Moisture Content and Solids Decomposition in As-Built Cell B

4.1.3 Summary of Solids Decomposition

The objectives of this section were to: (i) assess reproducibility between the cells and (ii) evaluate whether the solids composition data support the concept that operation of a bioreactor landfill can accelerate solids decomposition relative to a traditional landfill. The waste age is significantly older in the Retrofit cell relative to the As-Built and Control cells. As such, trends that include the influence of waste age should be most apparent in the Retrofit cells. However, as refuse decomposes the nature of the remaining degradable organic matter changes. Thus, the refuse in the As-Built and Retrofit bioreactor landfills cannot be assumed to be the same.

Analysis of cell reproducibility was important as it showed significant differences between As-Built cells A and B. Given the impracticalities associated with the operation of a full-scale landfill as a research site, it is not surprising that the cells were not perfect replicates however, this project will continue utilizing during the lifetime of this CRADA. As all solids data could be analyzed as a function of waste age, the need for replication was less important than cases where waste age is difficult to assess. In the case of the OLLB, it was possible to assign a waste age to individual samples on the basis of landfill fill records, a capability not afforded at many other study sites.

The available solids composition data document significant decreases in degradable solids as a function of waste age in the Retrofit cell. The average waste age in Retrofit cells A and B in 2005 was 3,044 and 2,955 days, respectively. In contrast, the average waste age for Control cells A and B in 2005 was 1,657 and 1,655 days, respectively. Thus, there is less time for trends to become apparent in the Control cell relative to the Retrofit cells. In 2005, the average moisture contents were similar in the Retrofit and the Control cells, although the recirculation of leachate in the Retrofit cells would be expected to provide some stimulation even if the average moisture contents are similar.

The slope of the CH:L and organic solids linear regression lines for the Retrofit cells were greater (i.e., more negative) than that for the Control cells as would be expected given that the Control cells were not operated to accelerate decomposition. However, the slopes of the BMP linear regression lines for these two

Table 4-4 Summary of Waste Composition Data for the As-Built cells and Assessment of Cell Replication

Sampling Year	Subcell	Statistical Parameter	Waste Age at Time of Sampling (days)	Moisture (%)	CH:L	BMP (mL CH_4/dry gm)	Organic Solids (%)
2001 & Early 2002	A	average	36	40.0	1.54	57.7	62.4
		stnd. dev.	(1)	4.5	0.77	18.5	12.1
	B	average	72	45.8	3.10	84.2	82.6
		stnd. dev.	(1)	7.0	0.66	22.3	4.2
	p-value		(1)	0.12	0.00	0.05	0.00
2002	A	average	290.3	41.9	0.96	26.6	41.9
		stnd. dev.	155.01	9.19	0.39	12.20	5.96
	B	average	207.5	41.5	1.00	20.3	37.5
		stnd. dev.	115.3	9.48	0.43	11.89	9.03
	p-value		0.05	0.90	0.76	0.08	0.054
2003	A	average	418	41.1	2.12	68.8	49.9
		stnd. dev.	175.48	8.3	0.55	25.0	11.0
	B	average	562	48.4	1.62	49.0	42.5
		stnd. dev.	123.4	16.7	0.51	21.7	10.1
	p-value		1.05E-05	0.0114	1.53E-05	9.05E-05	0.001
2004	A	average	22	28.1	2.99	75.9	56.4
		stnd. dev.	(1)	4.7	0.80	15.7	11.3
	B	average	76	39.5	2.40	97.8	58.9
		stnd. dev.	(1)	6.38	0.62	22.56	16.13
	p-value		(1)	0.0055	0.186	0.080	0.769
2005	A	average	730	39.9	1.46	44.2	40.4
		stnd. dev.	321.3	7.6	0.63	19.7	9.8
	B	average	545	39.0	1.79	62.9	51.9
		stnd. dev.	405.3	9.6	0.63	26.5	12.5
	p-value		0.048	0.708	0.045	0.002	0.00014

1. The 2001/early 2002 and 2004 sample sets were only six samples per cell. All samples were collected on the same day so the standard deviation is zero and a t-test is not appropriate. These samples were collected to characterize fresh refuse used to fill the cells.

test cells were similar. As will be discussed in Chapter 5, the LFG collected in the Retrofit cells appears to be greater than that collected in the Control cells, indicating that decomposition in the Retrofit cells may have been accelerated relative to the Control cells.

With regard to the behavior of samples from the As-Built cells, the calculated average waste age in As-Built cell A (730 days) and As-Built cell B (545 days) were significantly different and much lower than the average age in the Control cell (1,656 days). The young waste age in the As-Built cells makes it difficult to compare decomposition as trends would be expected to emerge over a period of five years or more. Nonetheless, As-Built cell A, which received more injected air than Cell B, exhibited more rapid decomposition (steeper slopes) than both As-Built cell B and the Control cell for all three measures of decomposition (CH:L, BMP, organic solids). This was also consistent with the higher moisture content in As-Built cell A (Figure 4-10). With respect to As-Built cell B, the linear regression slopes were not significantly different from zero which means that there was not a statistically significant decrease in CH:L, BMP or organic solids with waste age. Given the young age in As-Built cell B, it is difficult to document accelerated solids decomposition on the basis of the solids data alone. It is expected that if additional sampling and testing is performed in subsequent years, consistent trends with regard to the solids data will become apparent.

Finally, while the emphasis of this section has been to examine statistical evidence for accelerated biodegradation in the bioreactor landfill cells, it is also important to consider visible trends. Trends over time, in which the data were grouped by year, are presented in Figures 4-11 through 4-13. These figures illustrate trends in CH:L, BMP, and organic solids for both the As-Built A and Retrofit cells that are encouraging and support the supposition that the operation of a landfill as a bioreactor results in accelerated solids decomposition. Thus, while the statistical analyses were not overwhelming, this is likely a result of limited data, time period of sample collection, and waste heterogeneity, not the absence of accelerated decomposition. This observation is made in full recognition that the data set from the OLLB is perhaps the most comprehensive available to date. These data suggest the need for waste samples that are at least five years old to document decomposition. Going forward, it may be cost-effective to collect a smaller set of targeted samples of known waste age to provide information for a comparison of the effect of bioreactor landfill operation on solids decomposition.

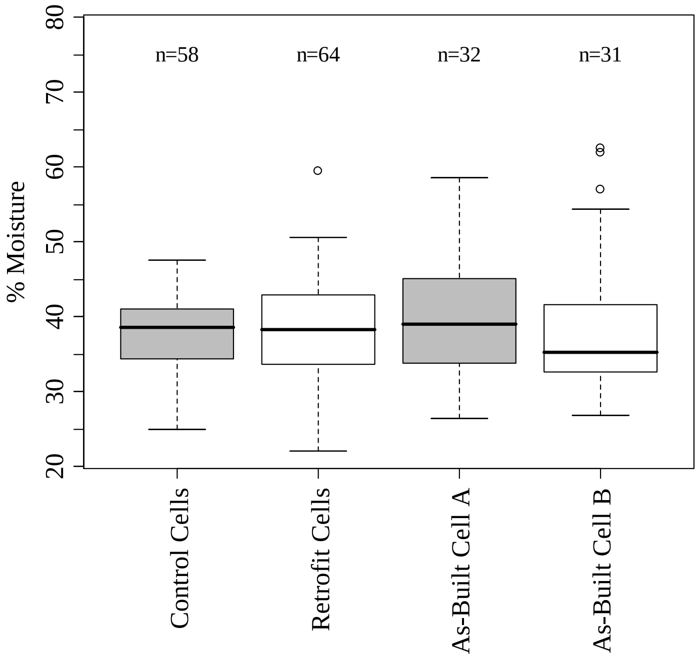
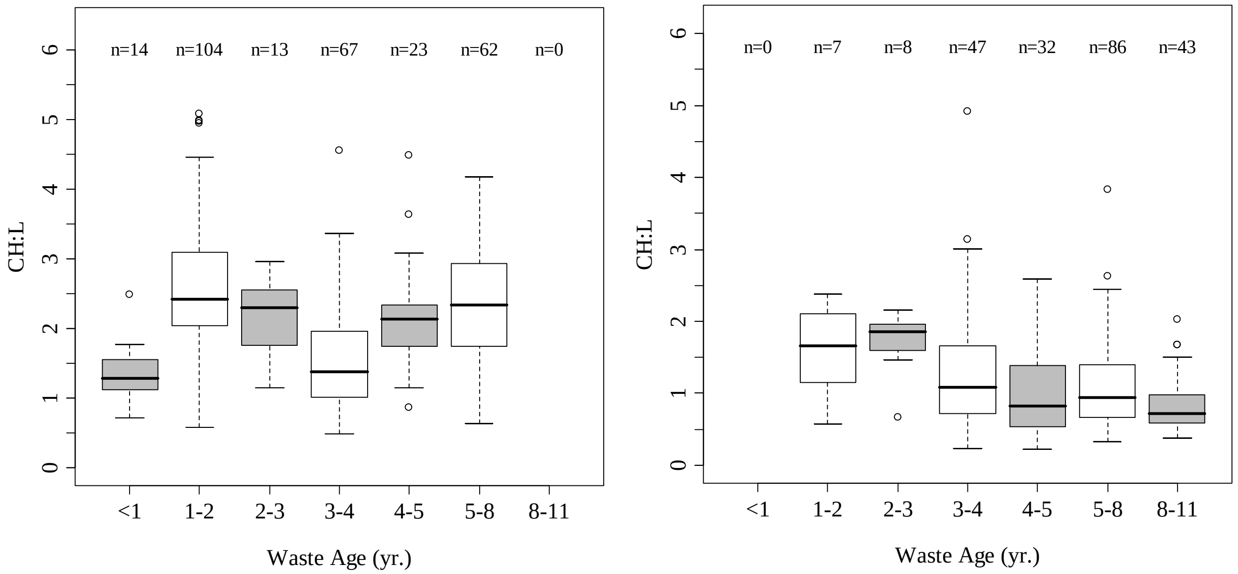
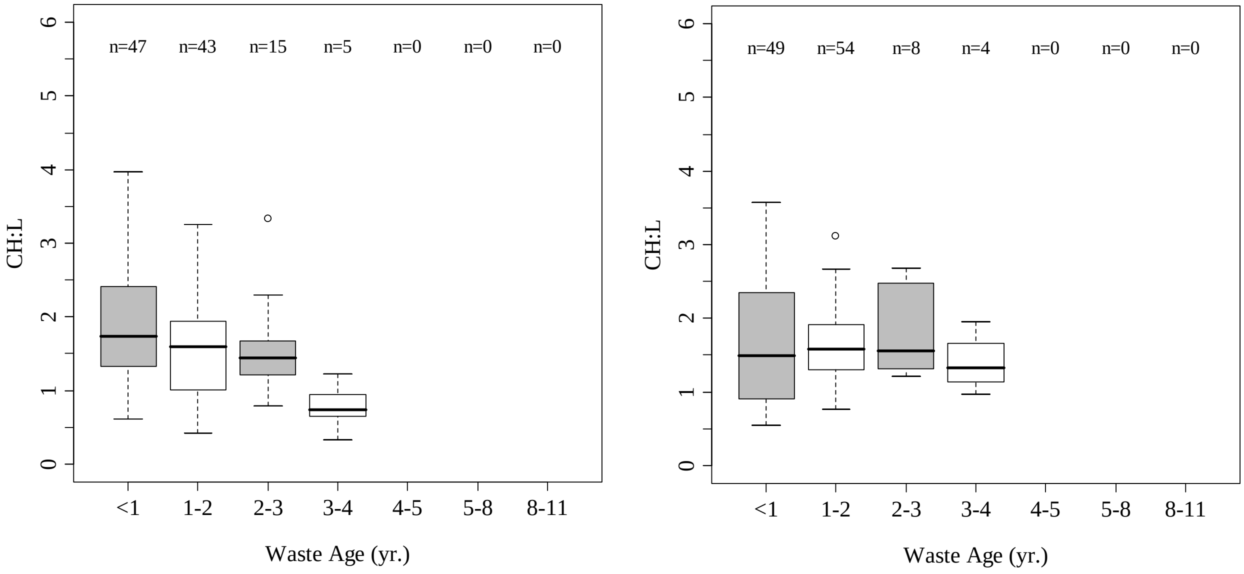


Figure 4-10 Comparison of Moisture Content in the Control, Retrofit, and As-Built Cells



Control cells

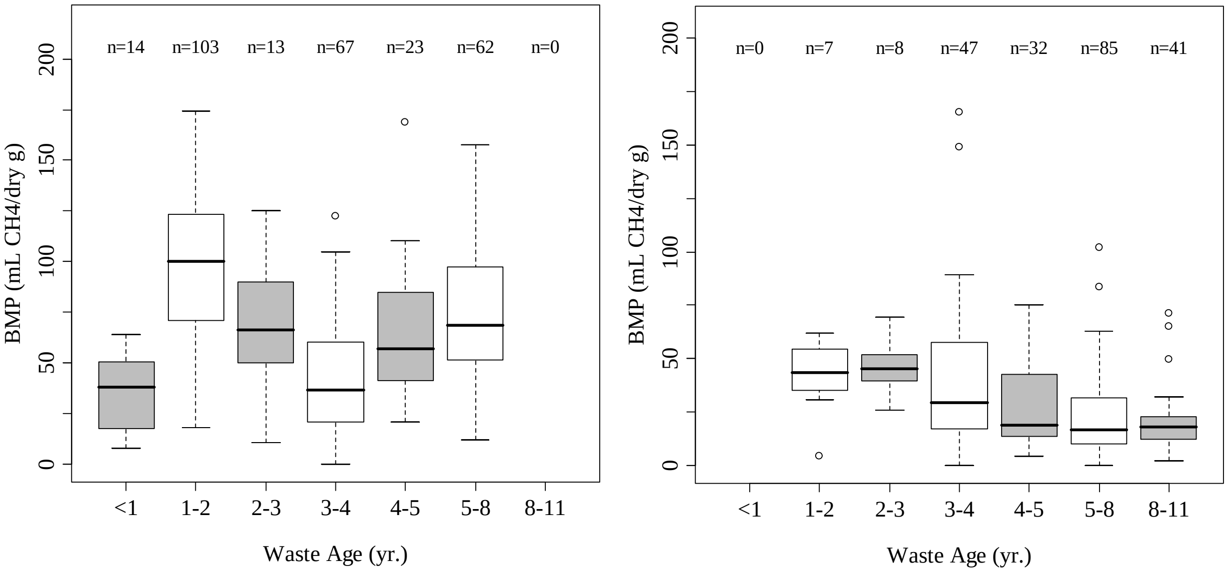
Retrofit cells



As-Built cell A

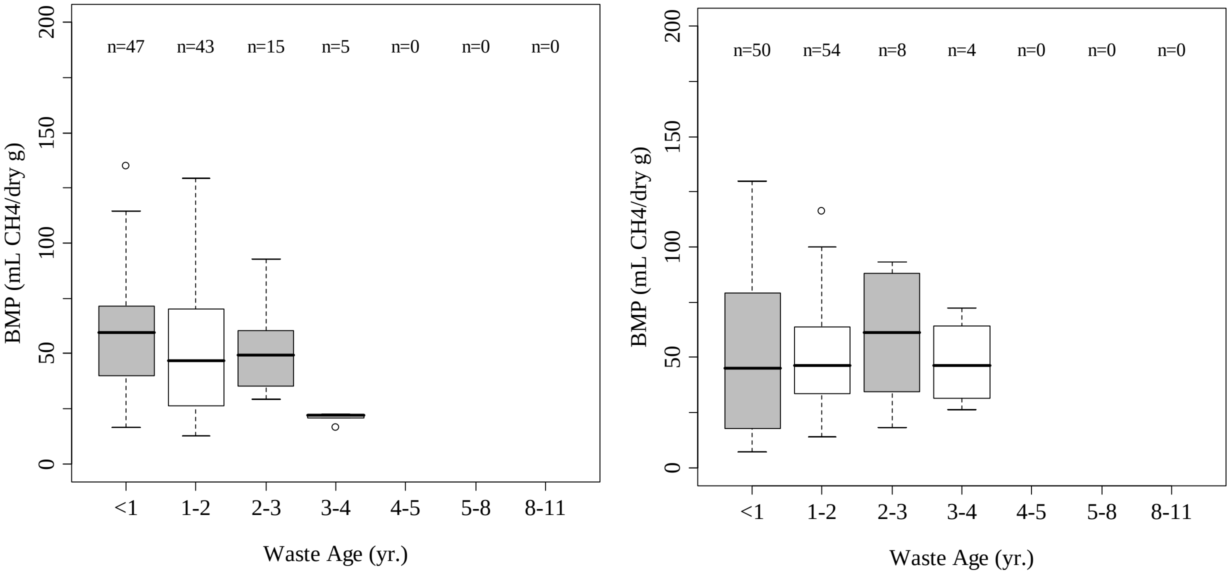
As-Built cell B

Figure 4-11 Trends in CH:L as a Function of Waste Age



Control cells

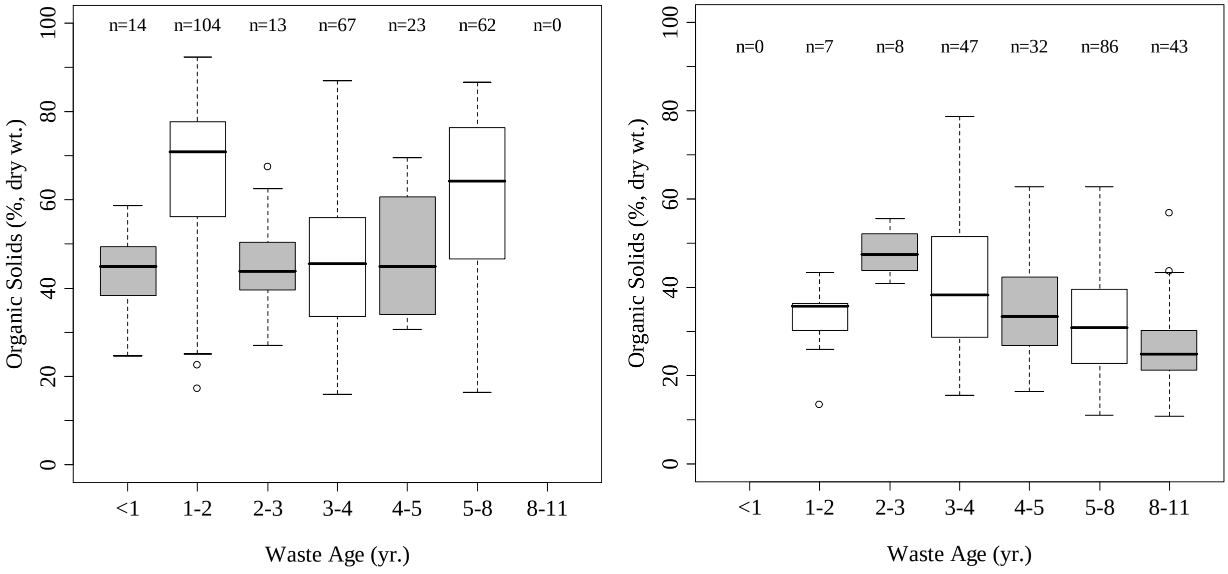
Retrofit cells



As-Built cell A

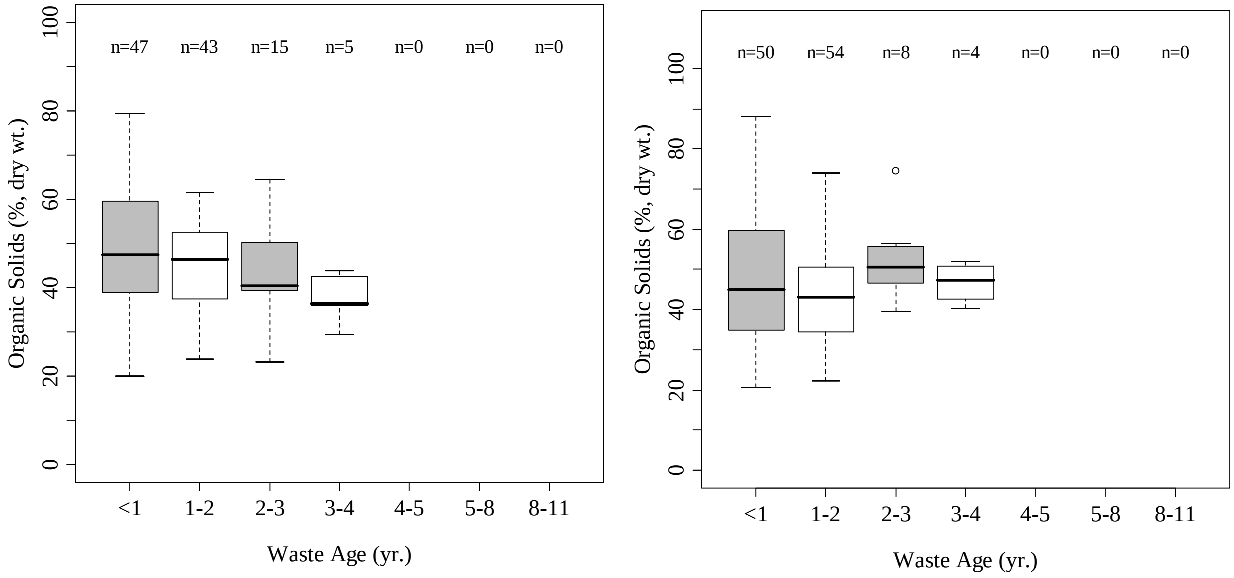
As-Built cell B

Figure 4-12 Trends in BMP as a Function of Waste Age



Control cells

Retrofit cells



As-Built cell A

As-Built cell B

Figure 4-13 Trends in Organic Solids as a Function of Waste Age

4.1.4 Solid Waste Surface Settlement

Accelerating waste settlement in a landfill unit is one of the key objectives of operating a landfill as a bioreactor. Moisture addition to the waste is intended to increase the rate of waste decomposition, resulting in accelerated waste settlement (and therefore a gain in airspace). Surface elevation data was collected for the different landfill units using GPS measurements. As discussed in Section 3.2.4, settlement in the Control and As-Built cells could not be estimated, since these units received waste for most of the study period, making an assessment of settlement as a function of waste decomposition alone difficult. Additional waste placement is not planned for the test areas. Periodic monitoring of settlement will continue at the site, and a discussion of settlement will be presented in the final report.

4.1.5 Landfill Temperature and Oxidation Reduction Potential (ORP)

As discussed in Chapter 3, instrumentation for measuring in-situ temperature of the waste and ORP was installed in the Retrofit and As-Built cells. Because of an installation defect, the majority of the thermocouples installed to measure temperature were heavily influenced by ambient temperature. As a result, the data collected for the Retrofit and As-Built cells were not representative of the waste temperature, and these data are not presented. Additionally, the majority of ORP probes returned data that indicated the probes did not function correctly; as a result, an analysis of ORP data is not presented in this report.

4.1.6 Solid Waste Slope Stability

A slope stability study for the Retrofit and As-Built cells was completed in March 2000. Results were presented in a report prepared by Vector Engineering, Inc. (Vector) titled: *Stability Analyses for Unit 7.4A/7.4B and Area 5 at the Outer Loop RDF, Louisville, Kentucky*. For the stability analyses, both the intermediate and final waste filling conditions were analyzed. Two potential stability failures were considered. The first failure condition assumes the failure surface to be based within the leachate collection system/geomembrane liner/compacted clay liner system interfaces. The second failure condition assumes failure to occur in the subgrade soils beneath the cells.

For the intermediate waste filling conditions, waste grades of 3H:1V and 3.5H:1V (horizontal to vertical) were analyzed for both static and pseudo-static conditions. For these analyses, a unit weight of 1041 kg/m^3 (65 pcf) was assumed and a friction angle of 33° for the waste was used. For the final waste filling conditions, the final design waste grade was assumed to be 4H:1V for both static and pseudo-static conditions. For these final conditions, a unit weight of 1361 kg/m^3 (85 pcf) and a friction angle of 25° for the waste were assumed.

For the stability analyses in the Retrofit cells, both existing (i.e., before stockpiling) and proposed final conditions (i.e., after stockpiling) were evaluated. The western slope of the stockpiled material intersected the existing eastern slope of the Retrofit cells. Stability analyses were evaluated for both the eastern and western side slopes under static conditions.

Based on the assumptions made in the stability study, it was concluded that selected waste grades for intermediate and final conditions in As-Built cell A and As-Built cell B are stable under static and pseudo-static conditions. Similarly, the existing and proposed conditions for waste grades in the Retrofit cell were stable under drained and undrained static conditions.

Liquid addition to the Retrofit and As-Built cells was initiated early in 2002 and is ongoing. For the monitoring period between 2002 and 2005, approximately 65,000 m^3 (17.4 million gallons) and 105,000 m^3 (27.8 million gallons) of liquid were introduced to the Retrofit and As-Built cells, respectively. Approximately 20 L (5.3 gallons) of nitrified leachate per Mg of in-place waste was applied in the Retrofit cells. Approximately 206 L (55 gal) of liquid per Mg of in-place waste was added to the As-Built cells. No stability problems have been reported for any of the landfill units at the OLLB to date. A slope stability analysis was not performed as part of this report. However, a follow-on study that utilizes data in this report may be beneficial and provide valuable information as to the potential for stability problems. A general discussion on slope stability is presented in Chapter 7

4.2 Moisture Addition

The purpose of this section is to provide a summary of the moisture balance assessments and a discussion of the calculated waste moisture content, liquid head on the liner, and measured moisture content within the study cells. In this section, “calculated moisture content” refers to the moisture content as determined using methods described in the U.S. EPA document *Example Moisture Mass Balance Calculations for Bioreactor Landfills* (U.S. EPA 2005c). The “measured moisture content” is the percent moisture content measured in the solid waste samples collected from the site throughout the study period (presented in Section 4.1). The discussion includes an assessment of the moisture balance calculations in the cells followed by a discussion regarding the leachate head in the LCS sump, which was used as an indicator of head on the landfill liner.

4.2.1 Moisture Balance

A moisture balance for each of the landfill cells was performed. Moisture balance calculations were performed for the Control, Retrofit, and As-built cells for the time period ranging from March 2002 to December 2005. The bulk waste moisture content was calculated for each of the landfill units. Furthermore, this calculated moisture content was compared to the one measured from field-collected samples of waste. The addition of leachate and liquids to the Retrofit and As-Built cells was expected to increase the moisture content of the waste. Field-measured moisture content was expected to exhibit large variability because of the spatial variation in waste hydraulic properties (i.e., waste heterogeneity) and the non-uniform wetting of the waste. It is noted that the method of solid waste sampling described in Chapter 3 may have impacted the liquid distribution in the bioreactor landfill cells. The advancement of the 0.9-m boreholes may have drilled through perched liquid zones, possibly leading to an improved liquid distribution. The degree, to which this occurred, if at all, is unknown.

For the moisture balance presented in this section, the “Liquid In” value is the summation of the estimated infiltration from rainfall, recirculated leachate, and added liquids. The procedure for incorporating infiltrated rainfall into the moisture balance was described in Chapter 3. The “Liquid Out” value is the leachate collected at the leachate collection sump. The difference between Liquid In and Liquid Out, ΔS, represents the change in moisture content due to liquids introduction. The bulk waste moisture content is calculated as follows:

$$\text{Moisture content} = M_i + \frac{\Delta S}{M_w} \times 100 \qquad \text{Equation 4-2}$$

Where:

M_i = Initial moisture content (%);

ΔS = Change in storage (tons of water); and

M_w = Wet weight of waste (tons).

Equation 4-2 was used to assess the moisture balance of the landfill units, and calculate moisture content of the waste for each landfill unit.

4.2.1.1 Precipitation

Rainwater infiltration into the solid waste is typically governed by the type of cover material and vegetation on the surface of the waste. At the OLLB, a vegetative cover was not constructed with the exception of the Retrofit cells. Precipitation data was collected by an on-site weather station. Figure 4-14 presents the mean monthly precipitation and the cumulative precipitation that was recorded at the site during the period from March 2002 to December 2005. The annual average precipitation at the OLLB is about 100 cm (40 in.). However, it is important to note that evapotranspiration is believed to be relatively high, ranging from 40 to 70 percent (based on HELP input parameters) depending on surface soil conditions.

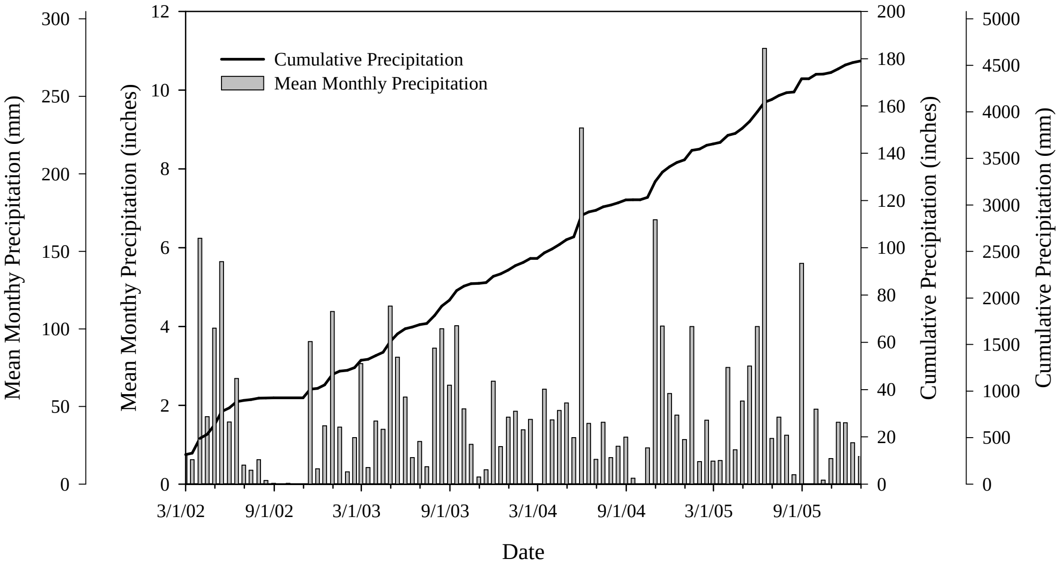


Figure 4-14 Cumulative and Mean Monthly Precipitation

4.2.1.2 Control Cells

The Control cells did not receive any supplemental liquids addition during the study. Control cell A and Control cell B were combined in this analysis because there was no hydraulic separation between the cells. However, since the cells were filled until 2004, infiltration from precipitation occurred during the monitoring period. The moisture balance and the calculated bulk moisture content of the waste in the Control cells are presented in Figure 4-15. The cumulative infiltrated volume reached about 3,000 m^3 (800,000 gallons) by December 2005 in this area. Infiltration to the Control cells was relatively low after waste acceptance ceased. The leachate generation in the Control cells was also relatively low and steady compared to the other landfill units during the monitoring period. Figure 4-15 shows no general seasonal patterns and indicates no general trends during the monitoring period. Prior to the middle of 2003, the calculated value of Leachate Out was higher than Leachate In, resulting in a net decrease in the calculated bulk waste moisture content from 32 to about 29.5 percent. However, after mid-2003, the rate of Leachate Out decreased, resulting in a relatively constant calculated bulk moisture content of about 29.5 percent. With infiltration being almost the sole source for Liquid In for the Control cells, the calculated moisture content showed a slight decrease over the study period. This decrease may be attributed to the small amount of infiltration that occurred following the completion of waste filling, as well as the increase in vertical stress from added waste, causing compression and release of the pore liquids. During the study period, the calculated mean and standard deviation of Liquid In per Mg of in-place waste for the Control cells were 2.8 liters/Mg (0.7 gallons/ton) and 1.5 liters/Mg (0.39 gallons/ton), respectively. The measured mean and standard deviation of Liquid Out per ton of in-place waste were 22.7 liters/Mg (6.0 gallons/ton) and 7.8 liters/Mg (2.1 gallons/ton), respectively.

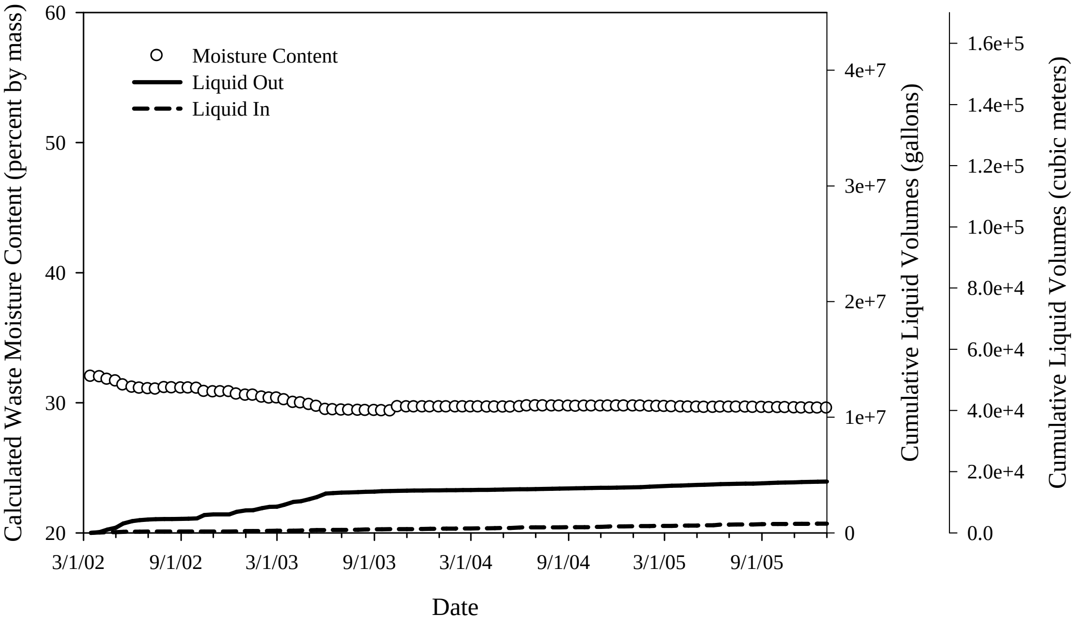


Figure 4-15 Moisture Balance and Calculated Waste Moisture Content of the Control Cells

4.2.1.3 Retrofit Cells

The Retrofit cells received nitrified leachate as well as the infiltrated liquids. There was no addition of waste into the Retrofit cells during the monitoring period. The moisture balance and the calculated bulk moisture content of the waste in the Retrofit cells are presented in Figure 4-16. Cumulative Liquid In reached about 76,000 m^3 (20.2 million gallons, approximately 15% infiltration) by December 2005, while cumulative Liquid Out was steady during the monitoring period and reached about 62,000 m^3 (16.2 million gallons) by December 2005. Infiltration volume for the Retrofit cells was relatively low compared to the As-Built cells because of the clay cover. Figure 4-16 shows no general seasonal patterns and indicates no cyclical trends during the monitoring period. Since Liquid In and Liquid Out were nearly identical, there was a small change in the calculated moisture content. The calculated bulk waste moisture content increased from approximately 37 to 38 percent as of December 2005. During the monitoring period, the calculated mean and standard deviation for Liquid In per Mg of in-place waste for the Retrofit cells were 20 liters/Mg (5.3 gallons/ton) and 9.5 liters/Mg (2.5 gallons/ton), respectively. The mean and standard deviation of the measured Liquid Out per ton of in-place waste were 13.5 liters/Mg (3.6 gallons/ton) and 8.8 liters/Mg (2.3 gallons/ton), respectively.

4.2.1.4 As-Built Cells

The As-Built cells received moisture through the addition of liquids and infiltration from precipitation. Liquids addition and infiltration occurred as waste was being placed as presented in Figure 4-17. The moisture balance and the calculated bulk moisture content of the waste in As-Built cell A and B are presented in Figure 4-17 and Figure 4-18, respectively. Infiltration volumes in the As-Built cells were the highest compared to the other landfill units. The primary reasons for the high infiltration volume were that waste placement occurred until 2005 and relatively high permeability compost was used as daily cover, in addition to the large volume of run-on because of the location of As-Built cells relative to the other units. The location of the As-Built cells resulted in a high percentage of run-on volumes to the As-Built cells, particularly from Unit 7.2 toward As-Built cell A and from the Control cells to As-Built cell B. The infiltration volumes comprised about 65 percent of the total liquid added to each of the As-Built cells. Cumulative Liquid In was greater than that of Liquid Out in the As-Built cells resulting in an increase in the calculated bulk moisture content of the waste.

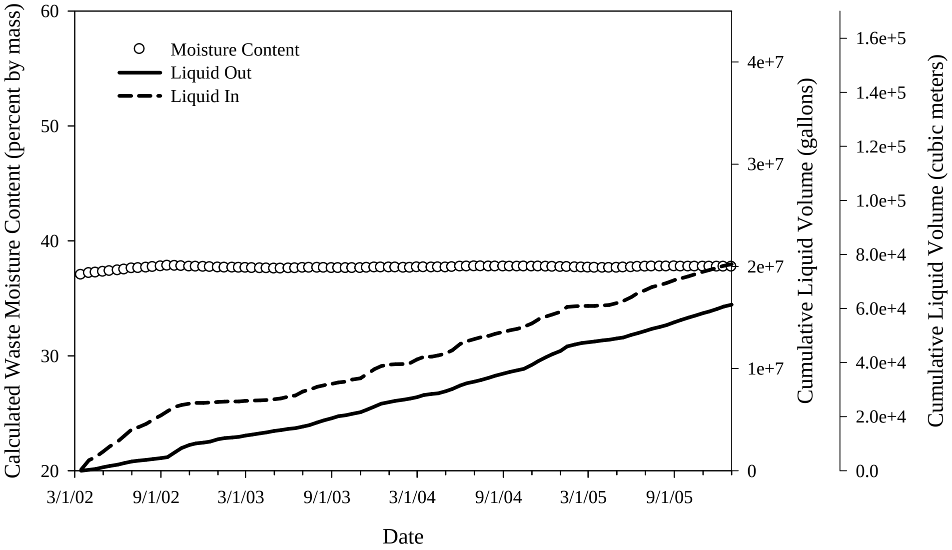


Figure 4-16 Moisture Balance and Calculated Waste Moisture Content of Retrofit Landfill Unit

For As-Built cell A, cumulative Liquid In reached about 152,000 m^3 (40.2 million gallons, approximately 62% infiltration) by December 2005, while cumulative Liquid Out reached about 80,000 m^3 (20 million gallons). Figure 4-17 shows no general seasonal patterns and indicates no cyclical trends during the monitoring period. A fluctuation in the calculated waste moisture content was observed in As-Built cell A. A rapid increase in the moisture content was noted around the middle of 2002 when the total waste mass was generally unchanged while the liquids introduction rate remained high. During the monitoring period, the mean and standard deviation of the calculated Liquid In per Mg of in-place waste for As-Built cell A were 247 liters/Mg (65.3 gallons/ton) and 47.2 liters/Mg (12.5 gallons/ton), respectively. The mean and standard deviation of the measured Liquid Out per Mg of in-place waste were 175.8 liters/Mg (46.5 gallons/ton) and 46.1 liters/Mg (12.2 gallons/ton), respectively.

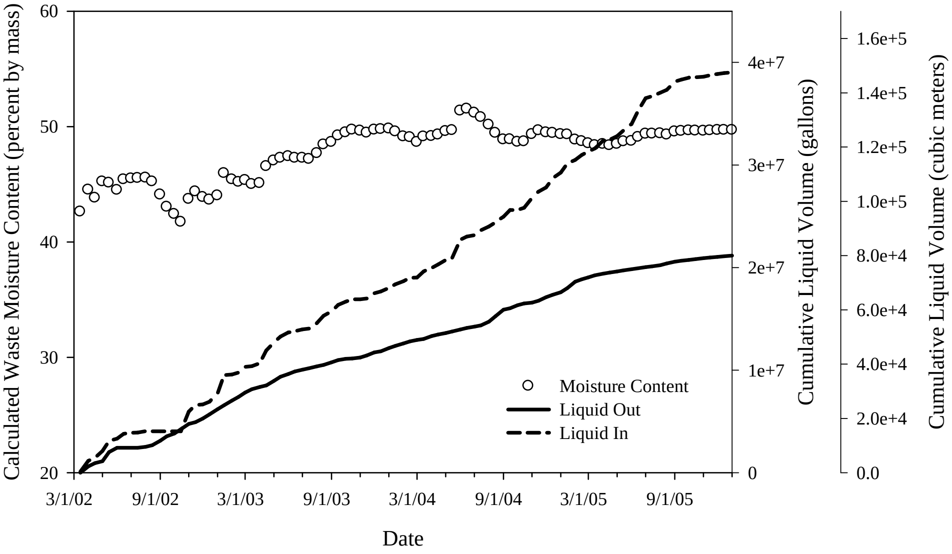


Figure 4-17 Moisture Balance and Calculated Waste Moisture Content of As-Built Cell A

For As-Built cell B, cumulative Liquid Out was relatively constant during the monitoring period. Cumulative Liquid In reached about 147,000 m^3 (39.0 million gallons, approximately 68% infiltration) by December 2005, while cumulative Liquid Out reached about 80,000 m^3. Figure 4-18 shows no general seasonal patterns and indicates no general trends during the monitoring period. The calculated bulk waste moisture did not show large fluctuations which increased from 43 percent to about 50 percent by December 2005. During the monitoring period, the calculated mean and standard deviation of Liquid In per Mg of in-place waste for the As-Built cell B were 164.0 L/ton (43.4 gallons/ton) and 52.9 L/ton (14 gallons/ton), respectively. The measured Liquid Out per ton of in-place waste mean and standard deviation were 106.2 L/ton (28.1 gallons/ton) and 34.0 L/ton (9.0 gallons/ton), respectively. The mean and standard deviation of the calculated bulk moisture content for As-Built cell B were 47.8 percent and 2.3 percent, respectively.

It is important to note that the calculated net increase in bulk moisture content in the As-Built cells above was conservative, based on the high liquid addition volumes. As described in Chapter 3, a layer of shredded tires was used between As-Built cell A and As-Built cell B during the construction of these cells until the first quarter of 2004, when it was noted that the shredded tires were acting as a conduit for leachate to drain quickly into the leachate collection system thus the use of shredded tires was discontinued. As shown on Figures 4-17 and 4-18, approximately 66% of the total leachate generation during the study period occurred prior to the first quarter of 2004 in the As-Built cells. Furthermore, the difference between the rates of increase for Liquid In versus Liquid Out is much more pronounced after the first quarter of 2004. Therefore, a portion of the Liquid Out used in the moisture balance calculation was likely overestimated, resulting in an underestimation of the ΔS.

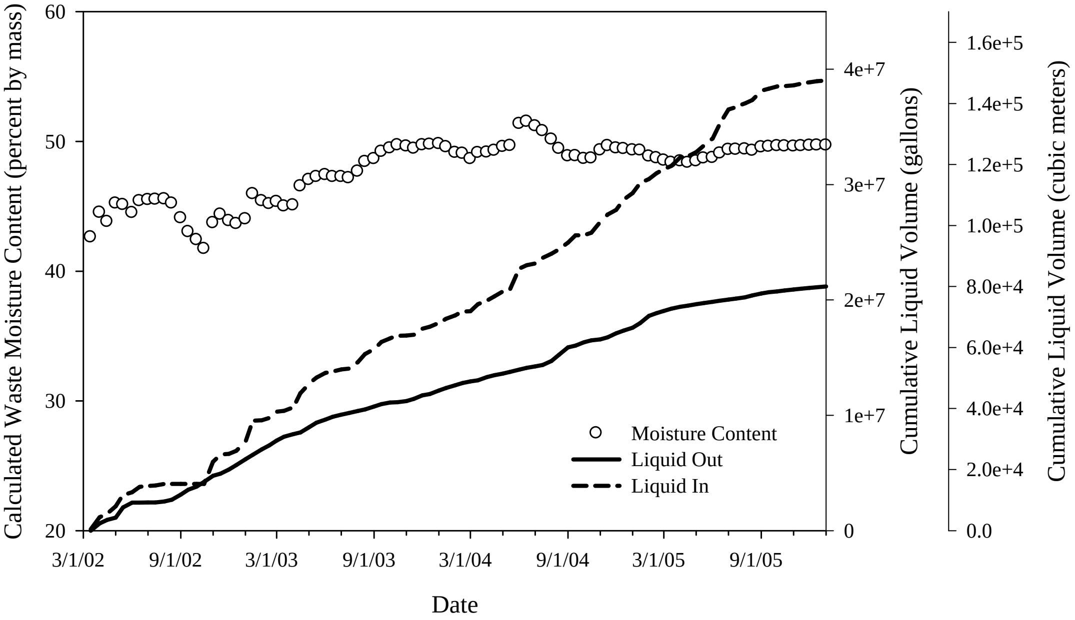


Figure 4-18 Moisture Balance and Calculated Waste Moisture Content of As-Built Cell B

4.2.2 Leachate Head on Liner

Under RCRA regulations, the head on the bottom liner of an MSW landfill should not exceed 0.3 m (1 ft). The main purpose of this regulation was to reduce risks associated with leakage of leachate from a landfill unit that could cause groundwater contamination. The potential for leachate head to build up on the bottom liner typically correlates with leachate generation, given that greater leachate generation rates would logically increase the potential for leachate accumulation of liquids on the liner. As mentioned previously, the leachate head presented in this section is the leachate head measured in the sump and not on the bottom liner itself. Caution must be taken when examining head on the liner data in this section since it is recognized that leachate head in the sump can be influenced by the size of the pump used to convey leachate from the leachate collection system, as well as the pump control system. Furthermore, the leachate head level in the sump may be affected by precipitation events (e.g., runoff from the landfill into either the sump or the vaults connected to the sump). The OLLB was permitted to have the leachate head in the sump temporarily exceed the regulatory limit of 0.3 m on days following heavy rainfall events, per the site's permit issued by Kentucky. Recognizing that the Control cells were considered as a whole in the moisture balance, leachate head in the sump of Control cells A and B were averaged for this assessment. Similarly, leachate head measured in the sump in the Retrofit cells was also averaged for these calculations.

4.2.2.1 Control Cells

The Control cells received liquids from infiltration only (i.e., the cells did not receive any supplemental liquids). Thus, leachate in the collection system is expected to be generated from infiltration and trends of leachate head are expected to correlate well with precipitation. The mean monthly leachate head in the Control cells is presented in Figure 4-19. The mean monthly leachate head was mostly below the regulatory limit. The mean and standard deviation of leachate head in the sump were 14 and 7.4 cm (5.5 and 2.9 in.), respectively. The leachate head and generation were generally higher prior to mid-2003, while waste was still being placed in the Control cells. Once waste placement ceased in 2003, both leachate head measurements and leachate generation decreased, as shown in Figure 4-20. The higher leachate head and generation rates prior to mid-2003 were likely caused by a portion of the runoff from the landfill being routed to the sump.

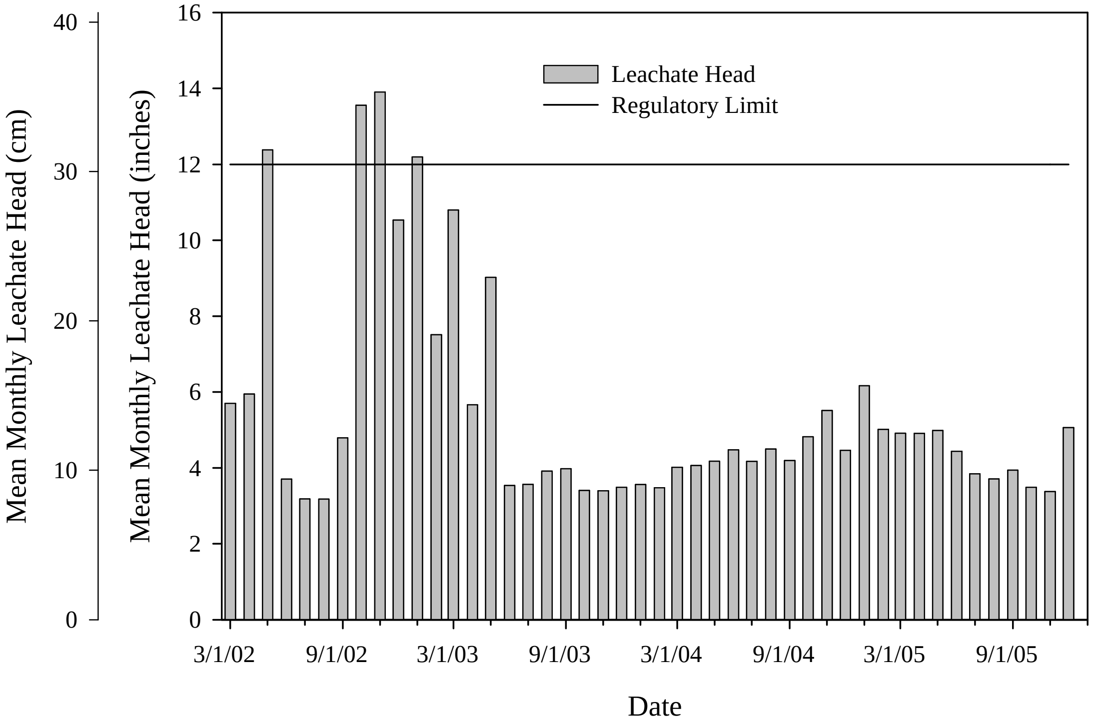


Figure 4-19 Mean Monthly Leachate Head on Liner of the Control Cell

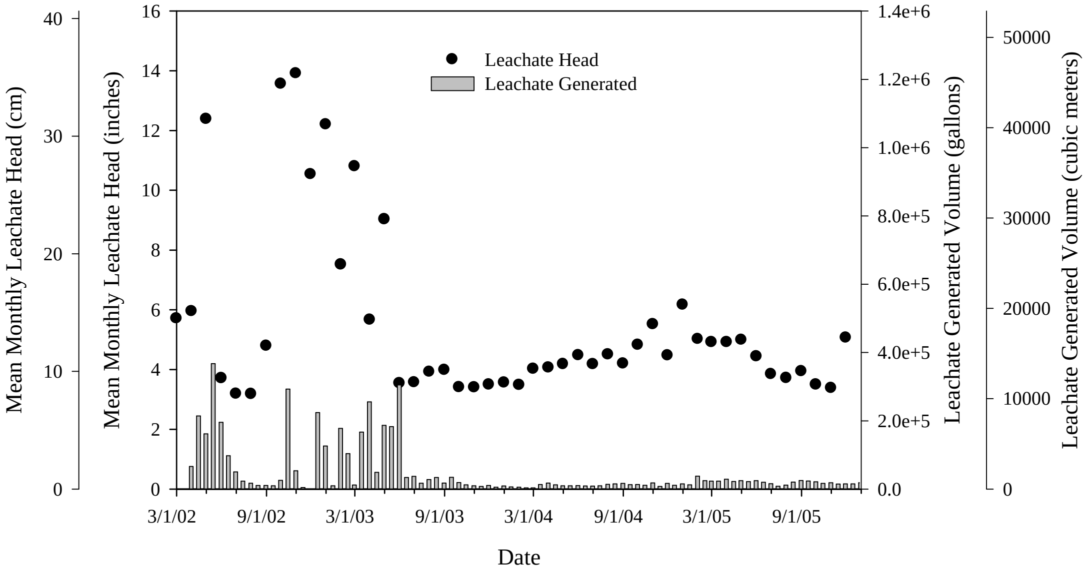


Figure 4-20 Mean Monthly Leachate Head and Leachate Volumes Generated in the Control Cell

4.2.2.2 Retrofit Cells

The Retrofit cells received moisture through the addition of nitrified leachate (beginning in March 2002) and infiltration from precipitation. The clay cap that was placed on the Retrofit cells resulted in a low infiltration volume relative to the As-Built cells. Since there was no hydraulic separation between the Retrofit cells with respect to liquid addition, the leachate head values as recorded from Retrofit cells A and B were averaged. Since the pressure transducers are located in the sumps of all cells, it is necessary to account for the elevation head in the sump. In the case of the Retrofit cells, the leachate sump was located at an elevation that added a pressure head of approximately 97 cm (40 in.). Thus, an “equivalent regulatory limit” is noted on Figure 4-21. The equivalent regulatory limit accounts for the additional 97 cm (40 in.) added to the transducer’s measurement caused by the higher elevation of the sump. The mean monthly leachate head in the Retrofit cells was generally below the regulatory limit. The mean and standard deviation of the leachate head were 95 cm and 25 cm (37.4 and 9.8 in.), respectively. The leachate head in the Retrofit cells was considerably higher than in the Control cells. The leachate head in the Retrofit cells is expected to be greater than in the Control cells since the Retrofit cells received additional liquids. The mean monthly leachate head correlates well with volumes of generated leachate in the Retrofit cells as presented in Figure 4-22. A temporary increase in leachate head correlated well with an increase in leachate generation towards the end of 2002 and at the beginning of 2005, as shown in Figure 4-22.

4.2.2.3 As-Built Cells

The As-Built cells received moisture through the addition of industrial liquids and infiltration from precipitation. Infiltration volumes for the As-Built cells were higher than those in the Control and Retrofit cells. This was the result of high infiltration allowed by the compost cover used for the As-Built cells during waste filling, as well as the higher volume of run-on from surrounding cells. Figure 4-23 and Figure 4-24 present the mean monthly leachate head in As-Built cells A and B, respectively. The mean monthly leachate head in the As-Built cells was below the 30 cm (1 ft) leachate head regulatory limit and similar to values measured in the Control cells. For As-Built cell A, the leachate head mean and standard deviation were 16 cm (6.4 in.) and 6.9 cm (2.7 in.), respectively. For As-Built cell B, the leachate head mean and standard deviation were 14.5 cm (5.7 in.) and 6 cm (2.35 in.), respectively. When compared to the Control cells, the addition of industrial liquids and the relatively large infiltration volumes did not have a significant effect on the head measured in the sump – Figures 4-19, 4-23, 4-24 indicate the number of times the 0.3 m (1 ft) threshold was exceeded (four, four, and one in the Control and As-Built cells A and B, respectively) during the study period. This is likely due to effective drainage of leachate in the cells’

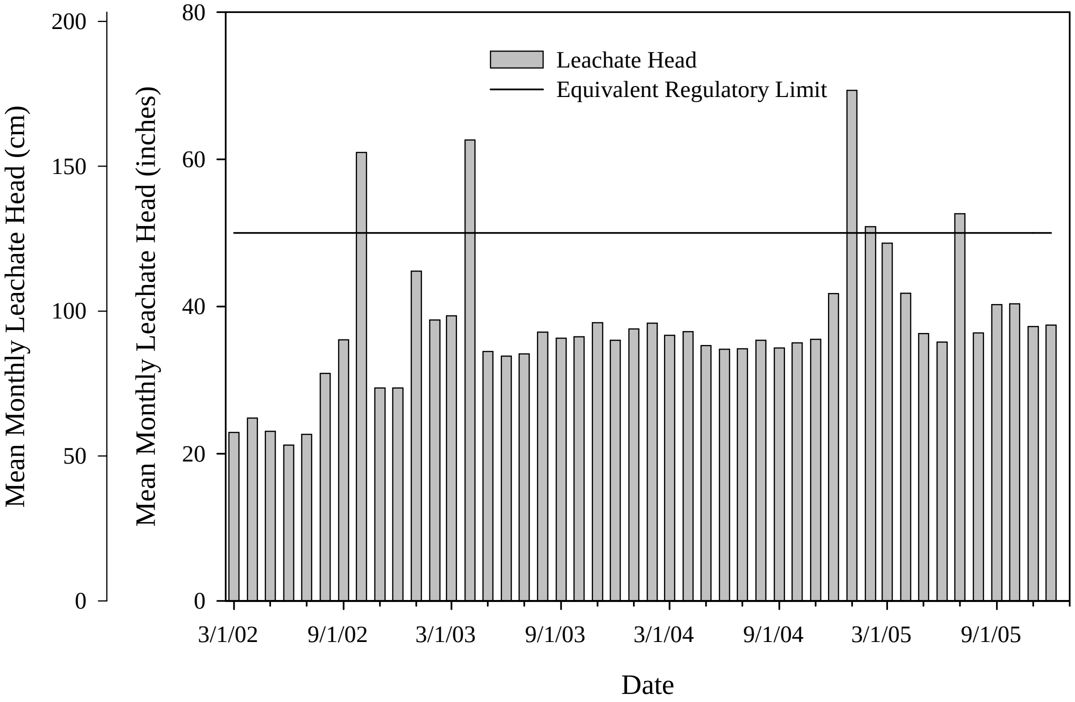


Figure 4-21 Mean Monthly Leachate Head on Liner for the Retrofit Cells

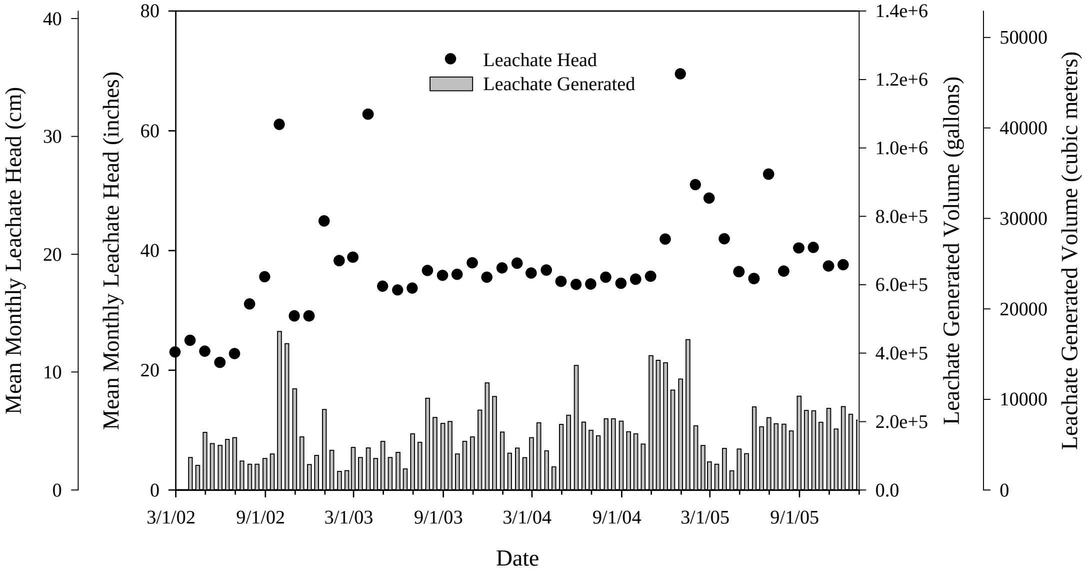


Figure 4-22 Mean Monthly Leachate Head and Leachate Generated Volumes in Retrofit Cells

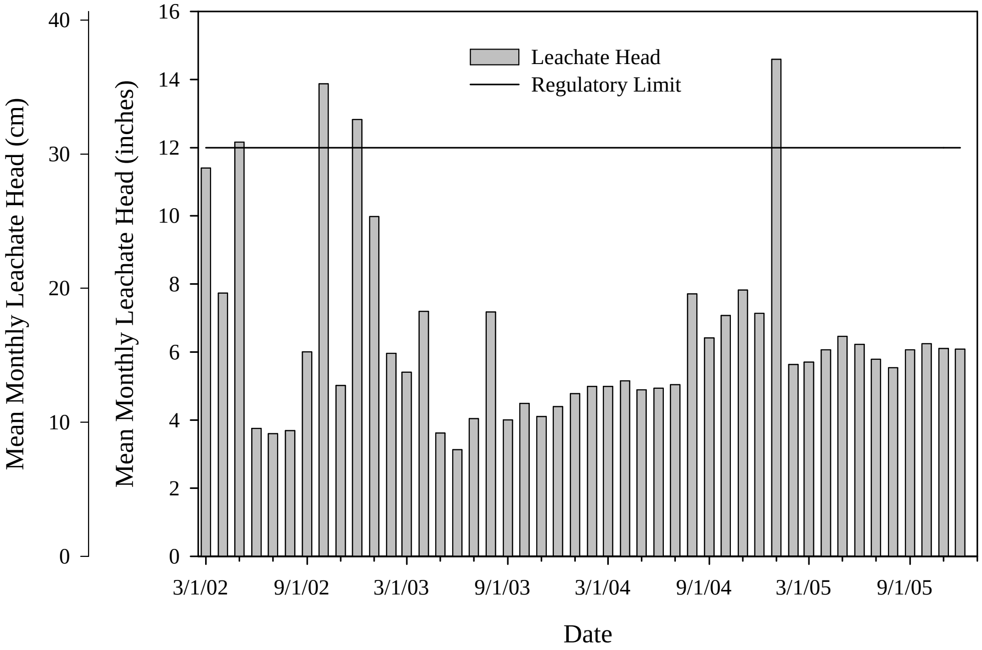


Figure 4-23 Mean Monthly Leachate Head on Liner of As-Built Cell A

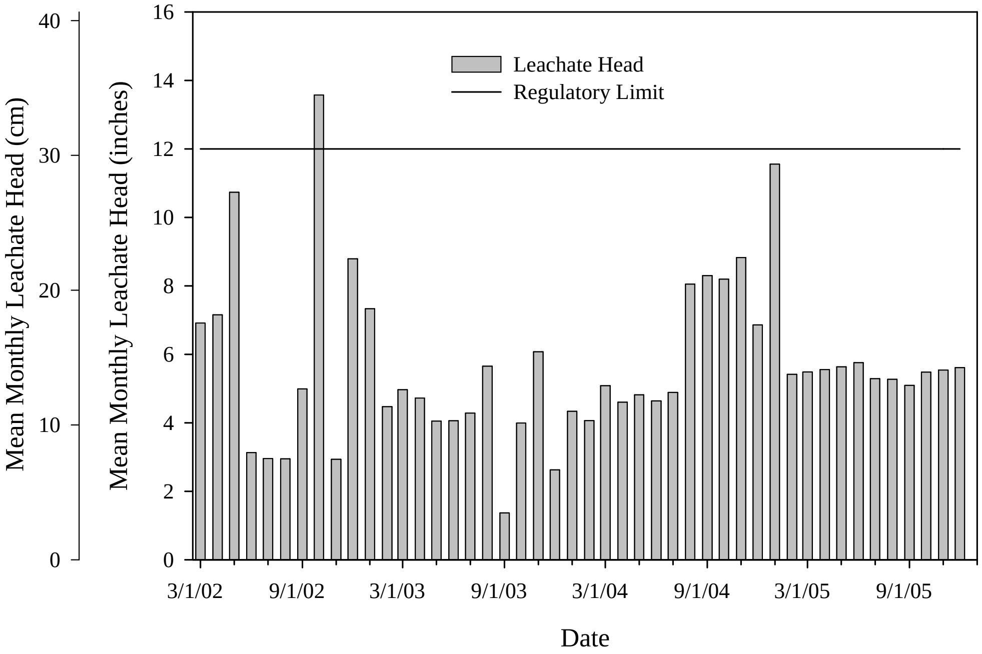


Figure 4-24 Mean Monthly Leachate Head on Liner of As-Built Cell B

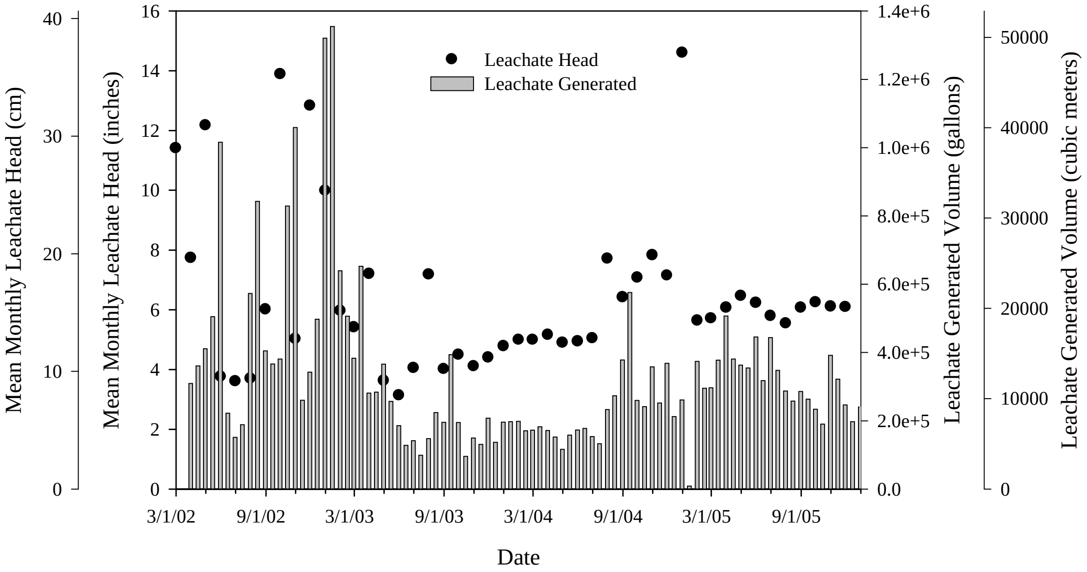


Figure 4-25 Mean Monthly Leachate Head and Leachate Generated Volumes in As-Built Cell A

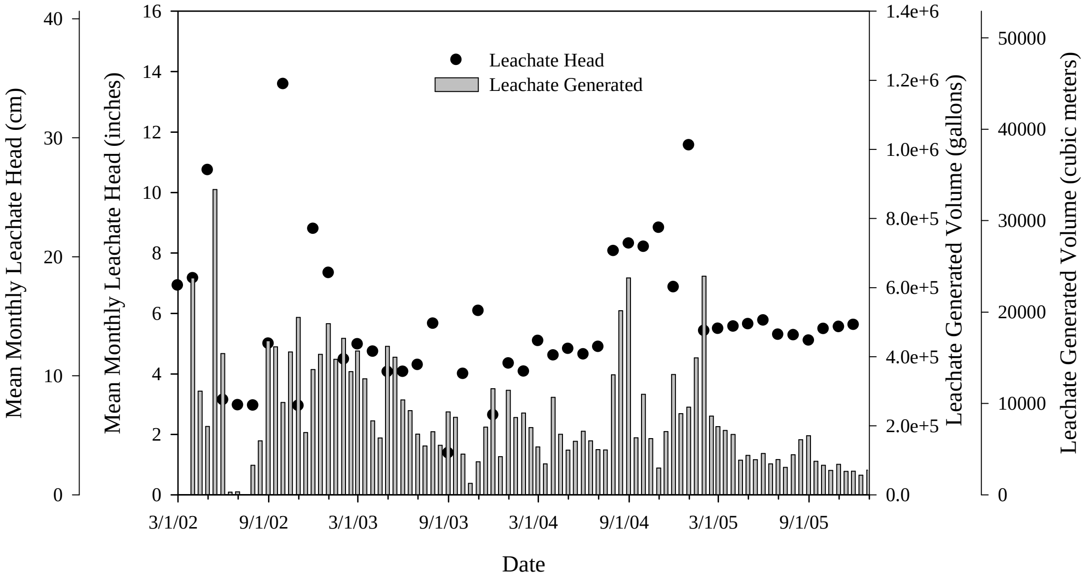


Figure 4-26 Mean Monthly Leachate Head and Leachate Generated Volumes in As-Built Cell B

leachate collection system that was specifically designed to handle the excess flow rate. Similar to the Control and Retrofit cells, the trend of leachate head of As-Built cell A and As-Built cell B appears to correlate well with trends in the generated leachate as presented in Figure 4-25 and Figure 4-26, respectively. An increase in leachate head correlated well with an increase in leachate generation for As-Built cell A at the end of 2002 and at the beginning of 2005. For As-Built cell B, an increase in leachate head correlated well with an increase in leachate generation in March 2002 and at the beginning of 2005. The elevated leachate generation in As-Built cell A and As-Built cell B was likely caused by a combination of: (i) a portion of the runoff being routed to the LCS during cell filling prior to the end of 2004; and (ii) the layer of shredded tires that was in use between As-Built cell A and As-Built cell B until the first quarter of 2004, which acted as a conduit for the injected liquids to enter the leachate collection system more quickly.

4.2.3 Measured Waste Moisture Content

This section describes statistical analyses that were conducted to evaluate moisture content trends with respect to waste age and sampling date. The moisture content of the waste was assessed on samples collected from each of the landfill units during the study period, as described in Section 4.1. The frequency of solid waste sample collection varied between the different landfill units. Samples collected from the Control and Retrofit cells in 2000 were included in this analysis. Waste age and moisture content were assessed using time plots and running linear regression fits of the data. Moisture content and sampling data were evaluated using box plots and performing multiple comparisons using Tukey's procedure. Details of the statistical analysis of these two methods are provided in Appendix C.

4.2.3.1 Measured Moisture Content versus Waste Age

Linear regression fits and time plots were used to evaluate the measured moisture content versus age and are presented in Appendix D. Inspection of the time plots indicates large variability in moisture content in all cells. This is also evidenced in the low adjusted-R^2 values, even though waste age is a significant predictor for all cells. The linear regression fits indicate that all cells had an increasing trend in moisture content with waste age. However, only the Retrofit cells' time plots indicate a definitive linear trend. Linear regression assumptions may not be met in the Control and As-Built cells.

The time plots for the As-Built cells appear to show moisture content levels increasing and then decreasing as waste age increases. It appears that the collection of additional older waste samples is needed to determine if a trend exists. The diagnostic plots show the residuals were not random in the As-Built cells. The diagnostic plots also show the residuals may not have been normally distributed in As-Built cell B. These characteristics make it difficult to definitively conclude if there was an increasing trend in moisture content with waste age in the Control and As-built cells.

4.2.3.2 Measured Moisture Content versus Sampling Date

For the analysis of measured moisture content versus sampling date, it was assumed that all sampled waste is similar for a specific sampling date and that the age difference in sampled waste between sampling dates is equal to the difference in sampling dates. One violation of this assumption would be if waste sampled in 2002 is actually older than waste sampled in 2003. Analysis of variance (ANOVA) summary tables and box plots were used in this analysis and are presented in Appendix C.

The ANOVA summary tables present the F-test of the null hypothesis that all means are equal versus the alternative hypothesis that there are at least two significantly different means. The other part of the summary tables provides Tukey multiple comparisons (i.e., comparisons of mean moisture content between each pair of sampling dates). A multiple comparison method is necessary to control the overall significance level since more than one significance test is being performed. Box plots are also provided to allow a qualitative assessment of each trend with sampling date.

For the Control cells, the F-test p-value indicates that at least two mean moisture content levels were significantly different. The Tukey multiple comparisons analysis indicates that mean moisture content levels were relatively constant across sampling dates except for the drop in 2002. In addition, the box plots did not provide evidence of a trend. Therefore, there is no evidence of a trend in the measured mean moisture content with sampling date in the Control cells.

For the Retrofit cells, the F-test p-value indicates that at least two mean moisture content levels were significantly different. The Tukey multiple comparisons indicated that the 2002 and 2005 mean moisture content levels were equal and both are significantly greater than the 2000 mean moisture content. The box plots did not provide any evidence of a trend. These results indicate there is no trend in the mean measured moisture content with sampling date in the Retrofit unit.

For As-Built cell A, the F-test p-value indicates there were no differences between mean moisture content levels. The box plots also indicated no differences present. Therefore, there is no evidence of a trend in the mean measured moisture content with sampling date in the As-Built cell A.

For the As-Built cell B, the F-test p-value indicates that at least two mean moisture content levels were significantly different. The Tukey multiple comparisons and the box plots indicate the 2003 mean was higher than the 2002 mean and the 2005 mean. Therefore, there is no evidence of a trend in the mean measured moisture content with sampling date in the As-Built cell B.

4.2.4 Evaluation of Calculated and Measured Moisture Content

Because solid waste samples analyzed for moisture content were measured for a given year with collection obtained in a single month, it was decided to compare these measured values to the calculated values for the entire given year. The calculated moisture content showed no patterns within a given year; therefore, the entire year is considered comparable to the measured values collected in a single month of that year.

A qualitative comparison of the distributions by year consisted of summary statistics and box plots. A quantitative comparison of the distributions by year consisted of a two-sample t-test and a nonparametric Wilcoxon Rank Sum test. The qualitative comparison is of the whole distribution while the quantitative comparison is of the mean of the distributions. The qualitative and quantitative comparison of the distributions is included in Appendix D.

Both the qualitative and quantitative comparisons indicate that measured moisture content was higher than the calculated moisture content for all years in the Control cells. All comparisons indicate that the measured moisture content and calculated moisture content were equivalent in both 2002 and 2005 in the Retrofit cells. The box plots and hypothesis tests indicate that the average calculated moisture content was higher than measured moisture content in the As-Built cells in all years except for As-Built cell B in 2002. While the box plots indicate the measured distributions span was smaller than the calculated distributions, the general conclusion must be that calculated moisture content was higher than measured moisture content in the As-Built cells.

A statistical summary including: (i) number of samples; (ii) mean moisture content; (iii) standard deviation; and (iv) coefficient of variation is presented in Table 4-5. The relatively large standard deviation in the measured waste moisture content is believed to be caused by a combination of the heterogeneous nature of the waste, the spatial variation in waste composition, and the varying macro-pore structure and resulting hydraulic properties within a given cell.

As shown in Figure 4-27, there was an overall increase in the mean measured moisture content in the Control cells of about five percent during the monitoring period, while the calculated moisture content showed a slight decrease. The amount of measured increase is unlikely to have occurred since the Control cells did not receive any addition of liquids. This may indicate that calculated values of the bulk waste moisture content are more accurate than the measured moisture content of discrete solid waste samples, or may be indicative of the inherent variability in the waste moisture content in different locations within the area. The mean measured waste moisture content showed an increase of about 2 percent for the Retrofit cells during the monitoring period. Figure 4-28 indicates that there was good correlation between calculated and measured waste moisture content in the Retrofit cells. This may have been due to the well-defined geometry of the Retrofit cells that resulted in relatively more accurate estimates of rainwater infiltrated volumes. However, it is recognized that the sampling frequency of solid waste samples in the Retrofit cells was relatively low as compared to other units.

In the As-Built cells, the measured moisture content revealed large spatial variation. The distribution of injected liquids will likely result in relatively wetter areas where the injected liquids follow preferential flow paths and accumulate, and the addition of air may have formed dry areas within the waste and removed some moisture via aerobic decomposition of the waste. The difference in calculated and measured moisture content of the As-Built cells may be caused by the assumptions taken for calculating the bulk waste moisture content. Infiltration and run-on volumes (estimated using HELP) to estimate the moisture balance of these cells in specific portions of the cells were difficult to estimate due to cell geometry. The measured waste moisture content showed large fluctuations with an average decrease of about 2 percent in the mean waste moisture content, as shown in Figure 4-29 (As-Built cell A) and Figure 4-30 (As-Built cell B). A decrease in the moisture content of the As-Built cells is doubtful because of the addition of relatively large liquid volumes into these cells. The calculated bulk waste moisture content appears to be a more realistic representation of the As-Built moisture content than the measured moisture content from waste samples taken from those cells.

As expected, there was lower variability in the measured moisture content of the Control cells as compared to the Retrofit cells and As-Built cells (refer to Table 4-1) since no additional liquids were added. Leachate generation and liquid addition to the Retrofit and As-Built cells resulted in large spatial variation of the moisture content, likely due to the non-uniform wetting of the waste. Thus, the variability in the measured moisture content in the bioreactor landfill cells was greater than that in the Control cells.

Table 4-5 Summary of Calculated and Field Measured Waste Moisture Content

	Parameters\Date	**2002**	**2003**	**2005**
Control Cells	Number of Samples	70	73	60
	Mean Measured Waste MC ± Stdev Coefficient of Variation (percent)	32.5 ± 5; 15.3	36.1 ± 5.9; 16.3	38 ± 5.3; 13.9
	Mean Calculated Bulk Waste MC ± Stadev Coefficient of Variation (percent)	31.5 ± 0.4; 1.2	29.7 ± 0.4; 1.3	29.6 ± 0.1; 0.3
Retrofit Cells	Number of Samples	84	NA	64
	Mean Measured Waste MC ± Stdev Coefficient of Variation (percent)	37.0 ± 7.5; 20.1	NA	38.8 ± 6.6; 17.0
	Mean Calculated Bulk Waste MC ± Stadev Coefficient of Variation (percent)	37.7 ± 0.2; 0.5	37.6 ± 0.1; 0.2	37.7 ± 0.1; 0.2
As-Built Cell A	Number of Samples	24	42	32
	Mean Measured Waste MC ± Stdev Coefficient of Variation (percent)	41.9 ± 9.2; 21.9	41.1 ± 8.3; 20.2	39.9 ± 7.6; 19.0
	Mean Calculated Bulk Waste MC ± Stadev Coefficient of Variation (percent)	49.3 ± 3.4; 6.9	46.1 ± 2.3; 5.0	50.3 ± 1.2; 2.4
As-Built Cell B	Number of Samples	31	56	31
	Mean Measured Waste MC ± Stdev Coefficient of Variation (percent)	41.6 ± 9.0; 21.6	48.6 ± 16; 33.5	39 ± 9.6; 24.6
	Mean Calculated Bulk Waste MC ± Stadev Coefficient of Variation (percent)	44.2 ±1.1; 2.5	47.6 ± 1.7; 3.6	49.1 ± 0.5; 1.0

1. NA = Not Applicable.

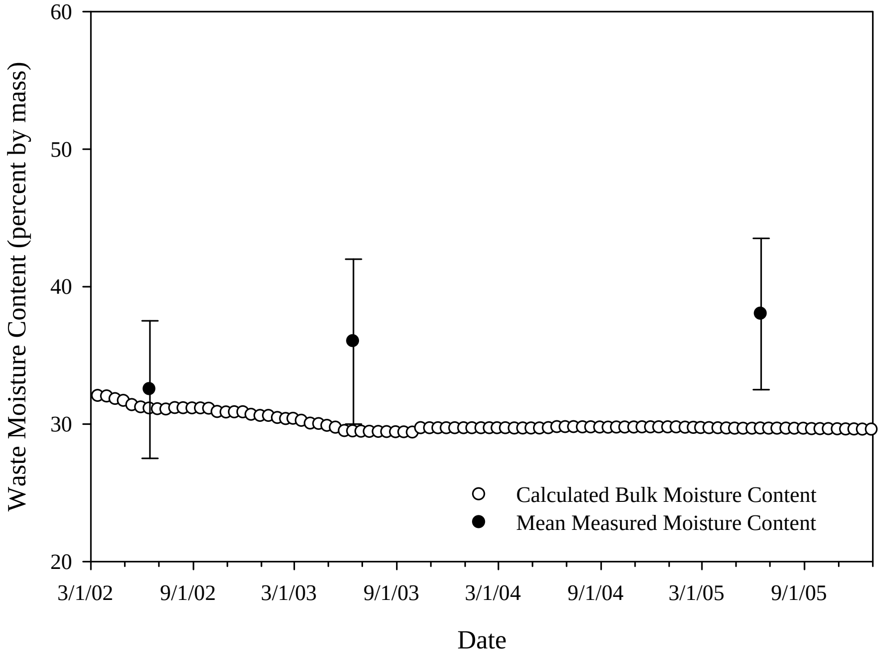


Figure 4-27 Calculated and Measured Waste Moisture Content in the Control Cells

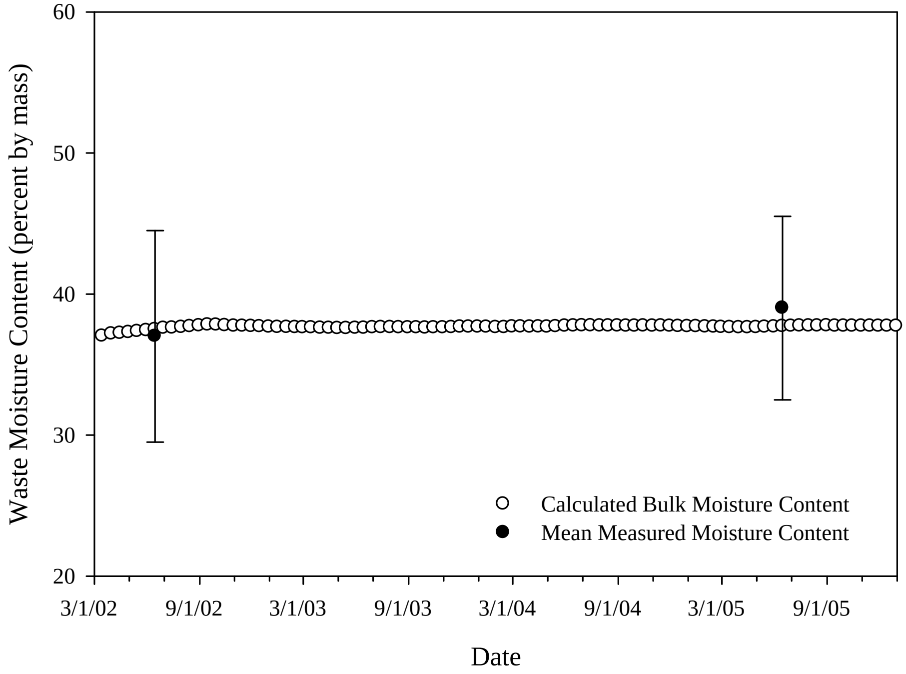


Figure 4-28 Calculated and Measured Waste Moisture Content in the Retrofit Cells

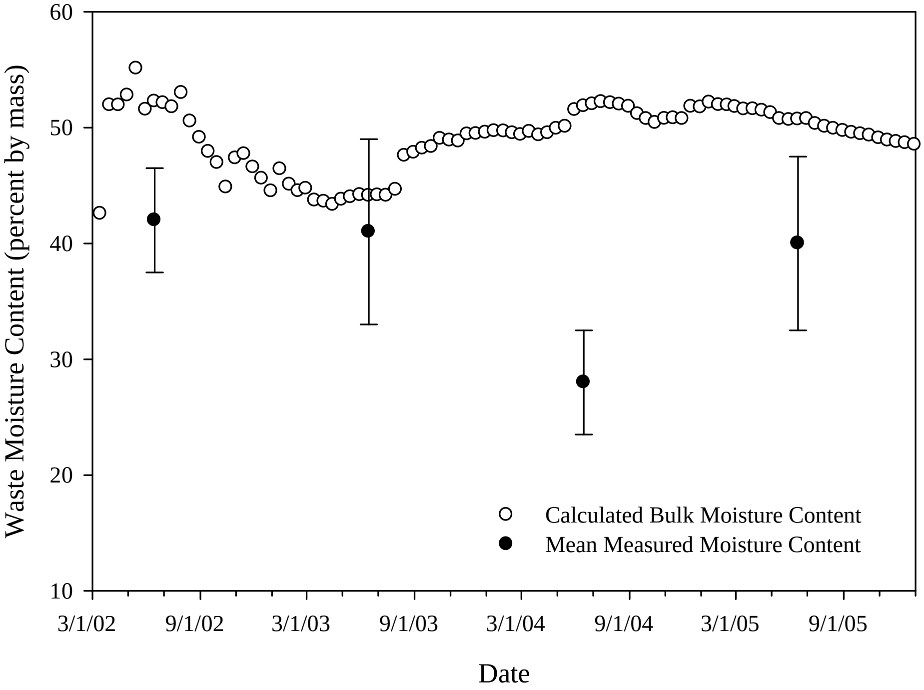


Figure 4-29 Calculated and Measured Waste Moisture Content in As-Built Cell A

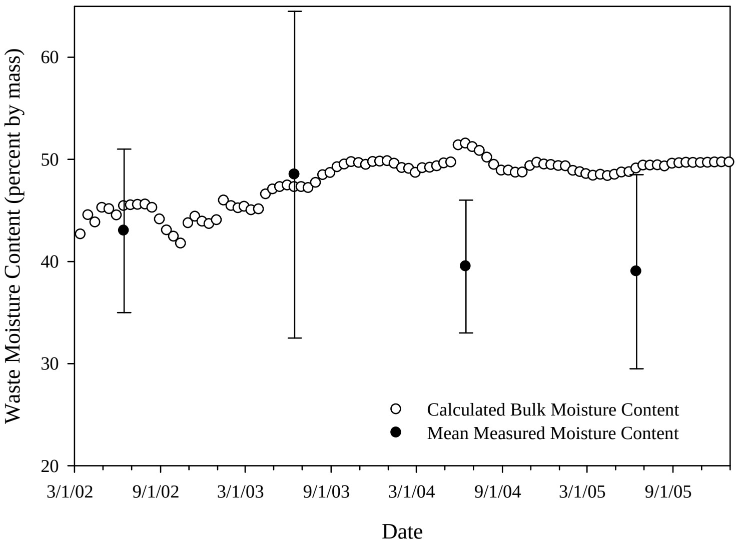


Figure 4-30 Calculated and Measured Waste Moisture Content in As-Built Cell B

4.2.5 Moisture Content Analysis Summary

A moisture balance of the different landfill units indicated an increase in the calculated bulk waste moisture content in the Retrofit and As-Built cells. The time plots for the calculated bulk waste moisture content showed no general seasonal patterns and indicated no general trends during the monitoring period. A decrease in the moisture content of about two percent was calculated for the Control cells, as a result of a larger Liquid Out volume versus Liquid In. By the end of December 2005, the calculated waste moisture content increased by about one percent in the Retrofit cells. The rate of increase in moisture content was relatively consistent over time. There was a relatively large variation in the calculated waste moisture content of the As-Built cells, as a result of the various assumptions considered in the estimate of infiltrated volumes into these cells, the ongoing waste placement in the cells, and the effects of air addition to the waste. By the end of December 2005, the calculated bulk waste moisture content had increased by six to seven percent in As-Built cell A and B, respectively. In making moisture balance computations, several estimates had to be made regarding the factors that influence infiltration. While it is believed that a net increase in moisture content occurred in the Retrofit and As-Built cells, it is difficult to verify the magnitude of the phenomenon, even moisture content data from solid waste samples.

Leachate head in the sump of the different landfill units was consistent with trends of leachate generation. Leachate head measurements were generally below regulatory limits and correlated well with trends of leachate generation. Overall, the mean leachate head measurements for all cells were below the regulatory limit of 30 cm (1 ft).

Trends in measured moisture content were assessed in two ways – moisture content versus waste age and moisture content versus sampling date. The first method provided some evidence of a trend in the measured moisture content with waste age, but the second method did not provide evidence of a trend in the mean measured moisture content with sampling date. The measured waste moisture content revealed a large variability because of the spatial variation in the waste. This variability was greater in the Retrofit cells and the As-Built cells compared to the Control cells.

The calculated bulk moisture content appeared to provide a more realistic estimation of the actual moisture content increase compared to the measured moisture content data. It appeared that on-going waste filling and the construction of tire chip layers at the edges of the As-Built cells reduced the magnitude of the expected moisture content increase, based on the estimated infiltration volume and the liquid addition volume. Overall, the results emphasize the large liquid volumes required to increase the moisture content of a landfill to the level cited in the literature as ideal for anaerobic waste decomposition.

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Chapter 5. Landfill Gas (LFG)

LFG quality and quantity were measured on an approximately weekly basis in accordance with procedures identified in Section 3 and the QAPP. This section consists of the following: (i) presentation of the LFG composition and flow data; (ii) comparison of field data and predicted LFG generation based on U.S. EPA's LandGEM at various waste decay rates; (iii) comparison of LFG flow data between the Control cells and the landfill bioreactor cells; (iv) presentation of non-methane organic carbon (NMOC) concentration data; (v) calculation of NMOC production based on LFG flow data; and (vi) calculation of NMOC production based on in-place waste data using LandGEM.

5.1 Landfill Gas (LFG) Composition

The quantity and composition of LFG is anticipated to vary with the stage of solid waste decomposition. However, since solid waste decomposition was believed to be occurring predominantly under anaerobic conditions at the time the gas measurements were obtained, LFG at the OLLB was expected to consist of approximately 55 percent by volume CH_4, 40 percent CO_2, 5 percent $N_{2,}$ and trace amounts of NMOCs (U.S. EPA, 1998). Often however, LFG is assumed to consist of only methane and carbon dioxide at 50% ratio. LFG was monitored on site using a LandGEM 2000 landfill gas analyzer. Sampling was performed approximately once per week during active gas collection for each cell. In accordance with the QAPP, triplicate gas readings were made for each sampling event at each sampling point. In this analysis, the mean of the triplicate readings is presented, and samples in which the gas flow was zero were eliminated from the analysis.

5.1.1 Control cells

As presented earlier in Chapter 3, LFG collection sampling at the Control cells began in January 2002. The data and analysis presented here show gas samples collected through February 2006. Gas samples were analyzed at two gas collection wells (GW) for each cell (GW A-1, GW A-2, GW B-1, and GW B-2). The number of triplicate sets of sample data evaluated varies between 116 (Control cells A-2 and B-2) and 147 (Control cell A-1). Summary statistics for the field gas samples taken from the Control cells are shown in Table 5-1. Statistically, the LFG composition was similar in each of the Control cells (GW A-1 and 2, B-1 and 2) and across duplicate cells (Control cells A and B).

The data presented in Table 5-1 shows LFG concentrations indicative of anaerobic decomposition; furthermore, the data are generally consistent (i.e., there was minimal variation in gas composition throughout the sampling period). To show the variation of gas composition over time within the Control cells, data collected between 2002 and 2006 were aggregated for each month. The results are shown in Figures 5-1 and 5-2 for Control cells A and B, respectively. The figures indicate that the gas composition of the primary LFG constituents was generally consistent throughout the sampling period. Additionally, the concentrations of O_2 and balance gas (i.e., N_2) were generally low for both cells throughout the sampling period, indicating minimal air intrusion and proper balancing of the gas collection system. It is also noted that the sampling location (well heads) may have played a role in minimizing the O_2 and N_2 concentrations by minimizing the effects of breaks and leaks in the header piping system.

5.1.2 As-Built cells

In As-Built cells A and B, LFG was sampled from the LFG extraction header pipe of each subcell starting in April 2003. Summary of gas composition statistics for As-Built cells A and B are presented in Table 5-2. Figures 5-3 and 5-4 summarize the temporal variation of the data presented in Table 5-2, and indicate substantial variability, particularly in comparison to the relatively consistent results from the Control cells. This variability is unusual given air injections into the cell. Potential sources of the erratic behavior include: (i) effects of air injection activities in the cells; (ii) leakage and air intrusion around the header pipes; (iii) air intrusion through the cover; and (iv) "over- pulling" of the well field.

Table 5-1 Summary Statistics for Gas Composition for Control Cells A and B

Sub Cell	Parameter	CH_4 (%)	CO_2 (%)	O_2 (%)	Balance (%)
GW A-1 (N = 147)	Mean ± Stdev	58±3	41±3	0.6±1	0.5±3
	Median	57	42	0.1	0.2
	Range	45-65	31-44	0-4.6	0-18
GW A-2 (N = 116)	Mean ± Stdev	58±34	42±3	0.2±0.3	0±3
	Median	57	42	0	0.2
	Range	48-68	33-48	0-2.4	0-11
GW B-1 (N = 116)	Mean ± Stdev	58±3	41±2	0.4±0.7	1.3±3
	Median	58	41	0.1	0.2
	Range	46-66	34-43	0-3.7	0-15
GW B-2 (N = 130)	Mean ± Stdev	57±2	41±1	0.2±0.4	0.8±2
	Median	57	41	0.1	0.3
	Range	43-62	38-44	0-1.9	0-10

Note: Each sample represents the mean of triplicate readings collected at gas collection well

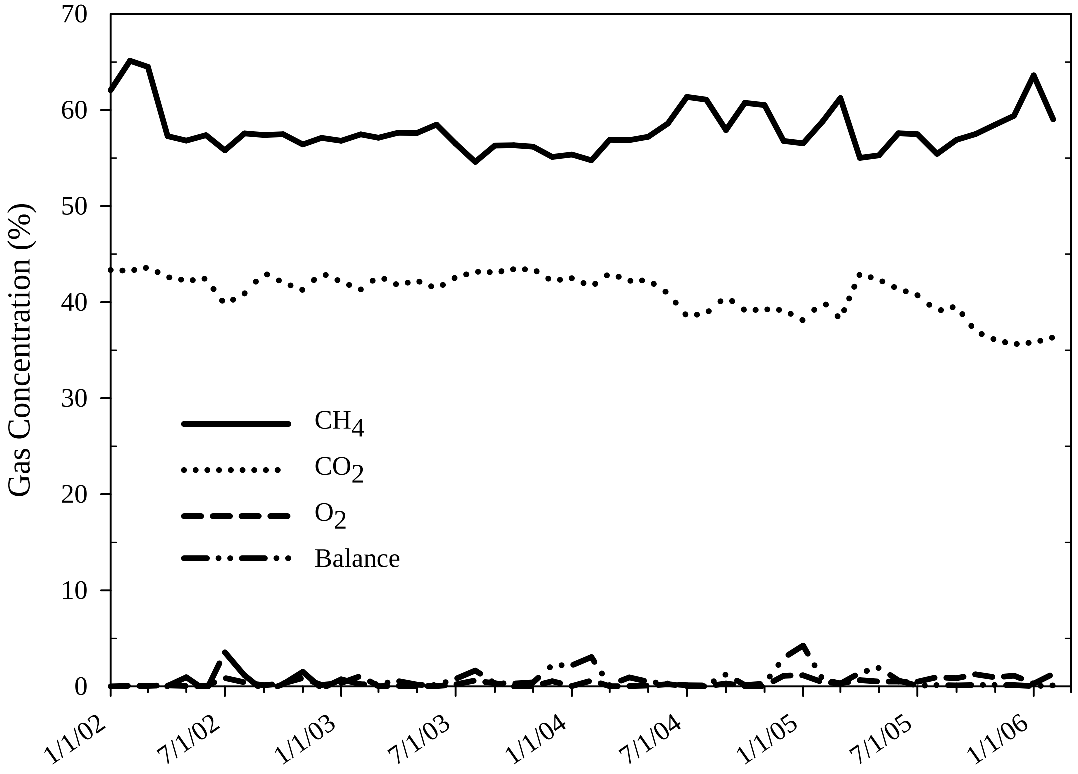

Figure 5-1 Monthly Average of Gas Composition for Control Cell A

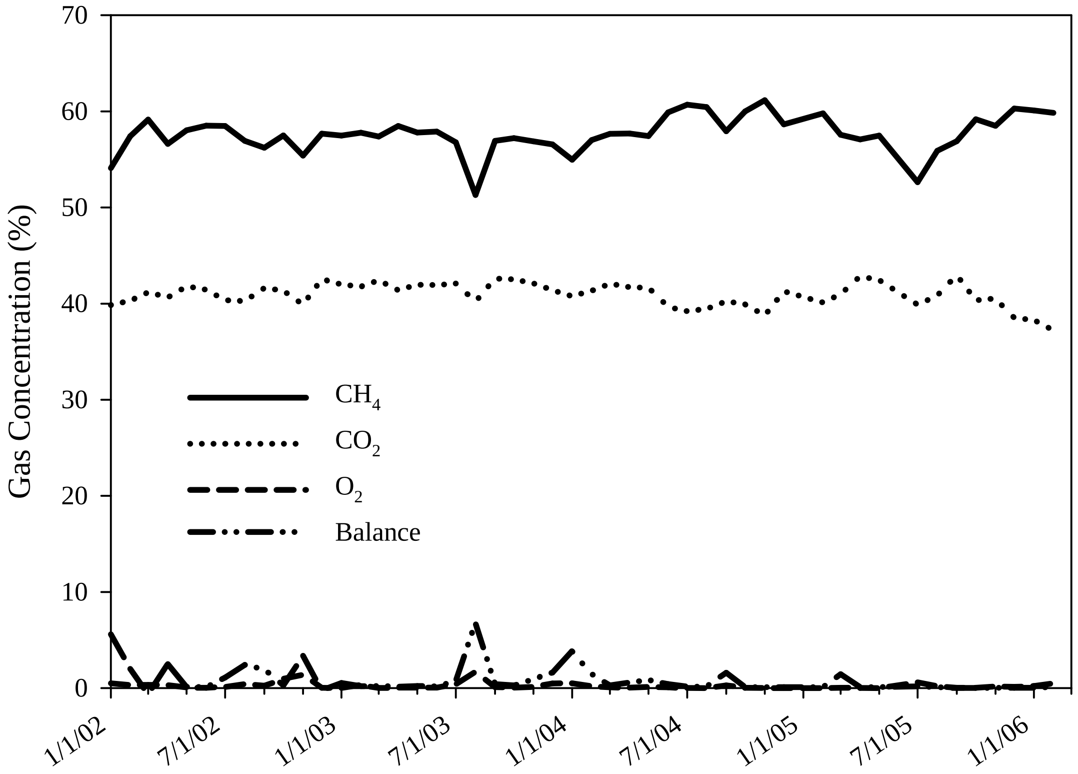

Figure 5-2 Monthly Average of Gas Composition for Control Cell B

The cause of this erratic behavior is likely a combination of the effects of air injection and sampling location. LFG sampling in the As-Built cells occurred in a header pipe, compared to the well heads in the Control cells, which allowed for leaks to play a role in LFG composition. The second reason is the aerobic/anaerobic operation of these cells. While air injection occurred at various times throughout the study period, it is likely that the months where more air was injected had an effect on the overall LFG composition. For example, in As-Built cell A, large-scale air injection activities occurred at various occasions as presented in Table 5-3. Figure 5-3 shows reduced CH_4 and CO_2 and elevated O_2 and balance gas during the same month where large air injection occurred. Large-scale air injection activities occurred in As-Built cell B. Again, Figure 5-4 shows that the CH_4 and CO_2 percentages were reduced, while the balance gas and O_2 concentrations were elevated at these times. It is interesting to point out that the O_2 to N_2 ratio during these times (assuming balance gas consists of only N_2) is (1 to 4) similar to that in ambient air.

Table 5-2 Summary Statistics of Gas Composition for As-Built Cells A and B

Sub Cell	Parameter	CH_4 (%)	CO_2 (%)	O_2 (%)	Balance (%)
Cell A (N = 127)	Mean ± Stdev	51±11	37±6.4	2.4±3	9.7±13
	Median	55	39	0.9	2.9
	Range	21-63	18-45	0-12	0.1-48
Cell B (N = 125)	Mean ± Stdev	52±9	37±6	2.1±3	9±11
	Median	54	39	1.1	5.5
	Range	5-82	4.2-45	0-18	0.1-73

Note: Each sample represents the mean of triplicate readings collected at gas collection header

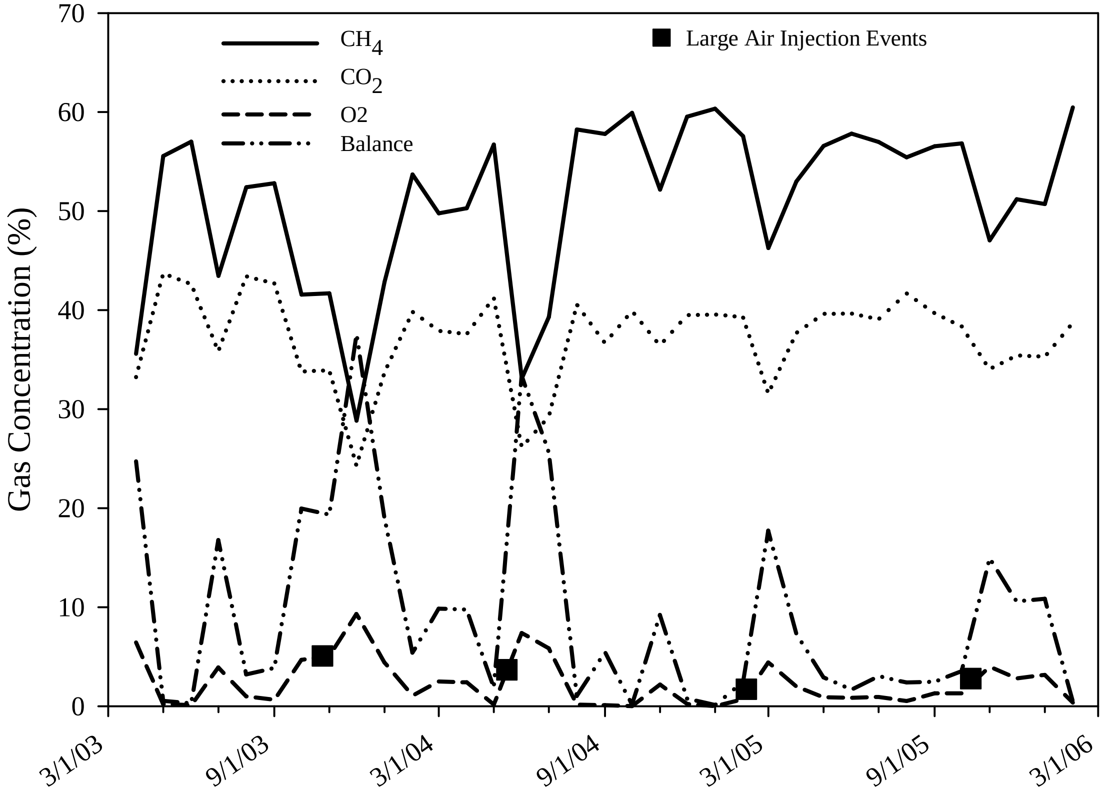

Figure 5-3 Monthly Average of Gas Composition for As-Built Cell A

Table 5-3 Notable Air Injection Dates for As-Built Cells A and B

Cell	**Month**	**Air Injected, m^3 (ft^3)**
As-Built cell A	11/2003	2.8x10^{5} (9.9x10^{6})
	6/2004	2.1x10^{6} (7.5x10^{7})
	1/2005	1.1x10^{6} (3.9x10^{7})
As-Built cell B	8/2003	5.7x10^{5} (2.0x10^{6})
	7/2004	7.7x10^{6} (2.7x10^{7})
	8/2005*	9.2x10^{6} (3.210^{8})

* Air injection occurred over a period of 6 month ending with the date indicated. Air injection occurred in equal volumes over that time period.

5.1.3 Retrofit Cells

In the Retrofit cells A and B, there was a single sample collection point in each cell. LFG sampling from the Retrofit cells began in November 2001 and summary statistics are presented in Table 5-4. Figures 5-5 and 5-6 show significant variability and inconsistency, although both cells seem to be exhibiting similar behavior. Potential sources of the erratic behavior include: (i) leakage and air intrusion around LFG header pipes; (ii) "over-pulling" of the well field and subsequent air intrusion through the cover; and (iii) watering out of gas collection wells. The most likely explanation is a combination of these factors, since watering out of gas collection wells can cause an imbalance in the vacuum applied to the landfill, resulting in over-pulling of the well field and subsequent air intrusion. These effects will be discussed in more details in Section 5.2.3. As with the As-Built cells, the O_2 to N_2 (assuming balance gas consists of only N_2) ratio is (1 to 4) is similar to ambient air throughout the monitoring period.

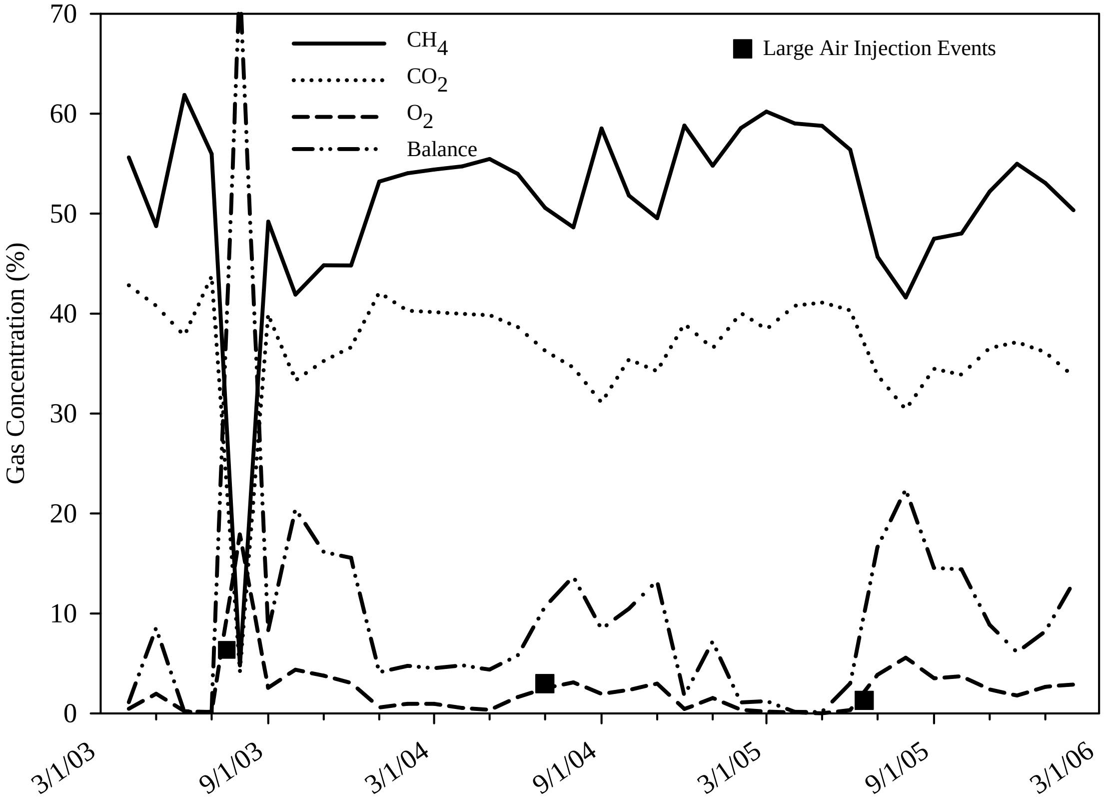

Figure 5-4 Monthly Average Gas Composition for As-Built Cell B

Table 5-4 Summary Statistics of Gas Composition for Retrofit Cells

Sub Cell	**Parameter**	**CH_4 (%)**	**CO_2 (%)**	**O_2 (%)**	**Balance (%)**
Cell A (N = 177)	Mean ± Stdev	49±9	35±6	3.3±3	11±12.3
	Median	51	36	2.7	7.2
	Range	4-63	3.2-46	0-19	0-74
Cell B (N = 140)	Mean ± Stdev	43±13	32±9.3	4.9±4.3	19±19
	Median	46	34	4	13
	Range	4-62	3.2-46	0-19	0-74

Note: Each sample represents the mean of triplicate readings collected at the header pipe of each cell

5.1.4 Landfill Gas (LFG) Composition Summary

In general, duplicate cells had statistically similar LFG composition, with CH_4 and CO_2 constituting the bulk of the LFG stream. Oxygen concentrations in LFG of the As-Built bioreactor landfill cells may not necessarily indicate a problem with the gas collection system. While some oxygen can be consumed in the process of aerobic degradation, the rate of air injection is much larger than what is needed for stoichiometric conversion; thus the majority of O_2 will pass through the system. However, the ratio of concentration of O_2 to N_2 in LFG of the Retrofit system at 1:4 (ratio of O_2 to N_2) is evidence of LFG collection problems. It is most likely that leaks in the header piping system played a large role in air intrusion as well as watering-out of LFG wells.

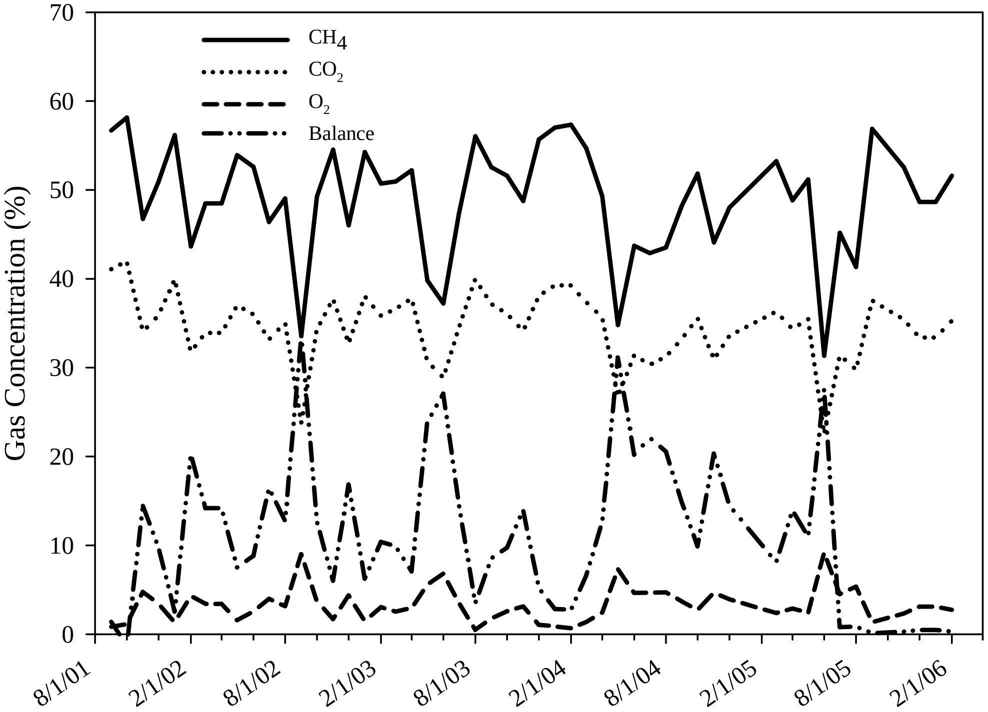

Figure 5-5 Monthly Average of Gas Composition for Retrofit Cell A

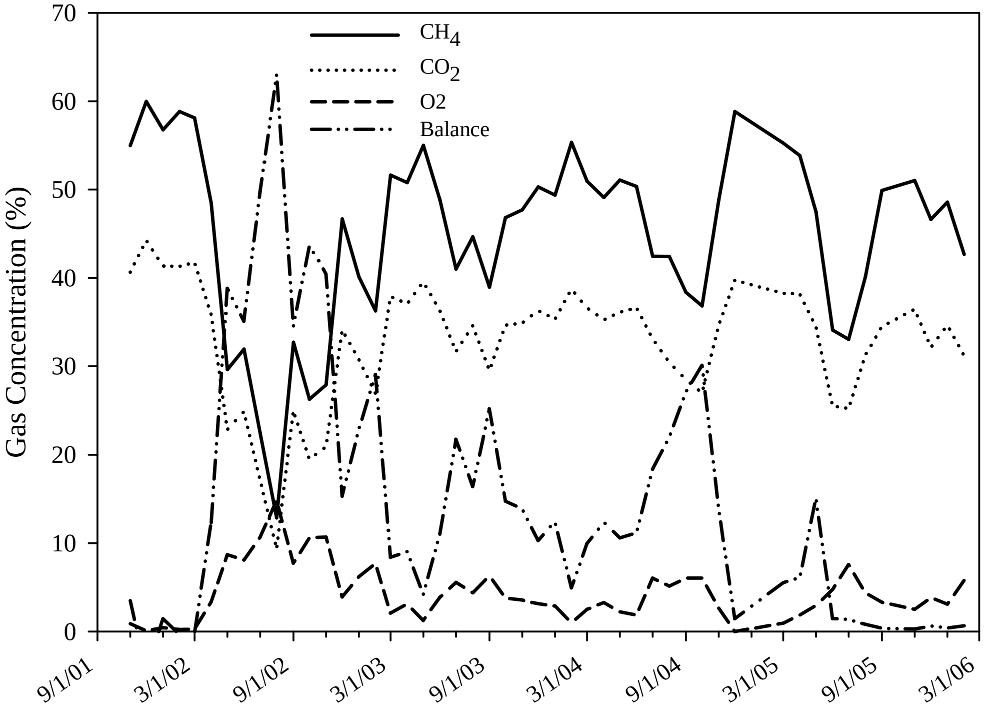

Figure 5-6 Monthly Average of Gas Composition for Retrofit Cell B

5.2 Measured Methane Production and LandGEM Model Predictions

For this section, the actual LFG collection rates (i.e., field data) were compared to predicted gas generation rates modeled in the U.S. EPA's LFG production model, LandGEM. LandGEM models landfill gas generation using a first-order decay equation. Detailed information regarding the parameters and assumptions used in LandGEM can be found on the U.S. EPA's website (http://www.epa.gov/ttn/catc/dir1/landgem-v302-guide.pdf). The equation used by the model to calculate LFG generation is similar in mathematical form to Equation 5-1:

$$Q = 2\sum_{i=1}^{n}\sum_{j=0.1}^{1} kL_o\left(\frac{M_i}{10}\right)e^{-kt_{i,j}} \qquad \text{Equation 5-1}$$

Where:

Q = LFG generated (m^3/yr);

k = first order waste decay rate (yr^{-1});

L_o = CH_4 generation potential (m^3/Mg waste);

M_i = waste mass placement in year i (Mg); and

$t_{i,j}$ = time (yr).

LandGEM allows the user to input various parameters, including waste mass placement (M_i), waste decay rate (k), and the CH_4 generation potential (L_o). One cited benefit of landfill bioreactors is the acceleration of the waste decomposition rate (i.e., higher k) (Reinhart and Townsend 1998). The objectives of the analysis presented in this section are to: (i) estimate an approximate k for each cell based on gas collection data; (ii) compare the actual landfill gas generation rates to those predicted using LandGEM; and (iii) compare the k values based on field data to the expected k values for landfill bioreactors as reported in the literature.

For the purposes of this analysis, waste mass inputs used in LandGEM for each cell are presented in Table 5-5. These values were calculated using waste receipts at the site. Model default values of L_o or site-specific estimates of L_o may be used in LandGEM. The U.S. EPA's compilation of pollutant emission factors, AP-42, states *"Estimation of the potential CH_4 generation capacity of refuse (L_o) is generally treated as a function of the moisture and organic content of the refuse."* Moisture content and BMP (i.e., a measure of the CH_4 yield of an organic material during anaerobic decomposition) data from fresh waste samples taken at the site in 2004 were available and were used to calculate a site-specific L_o.

Since the waste placed in each cell at OLLB was primarily MSW, it was assumed that the BMP and moisture content results of the fresh waste were indicative of waste placed in all cells. It is noted that the site specific L_o (59 m^3/Mg-wet) is lower than the LandGEM default L_o values for wet and conventional landfills (96 and 100 m^3/Mg (3,000 and 3,200 ft^3/ton), respectively).

The LFG flow rate and volume collected at OLLB, like any other landfill, represents the fraction of the gas captured by the LFG collection system. Thus, the collected LFG is generally less than the LFG generated since collection systems do not operate at 100 percent collection efficiency (CE). Rather, AP-42 states that reported CEs typically range from 60 to 85 percent, with a 75 percent CE being the value that is most commonly assumed. To this end, each of the subsequent sections will compare the following to the LandGEM-predicted gas generation rate: (i) the raw field data collected; and (ii) transformed field data, using the assumption that the gas samples represent a collection system operating at 75% CE. To accomplish this latter comparison, the collected LFG was divided by 0.75 to calculate the landfill gas generation rate. It is noted that this procedure does not follow U.S. EPA Method 2E for estimating a site-specific gas generation rate. The sites actual CE can be higher or lower than 75%, but for the purposes of this analysis 75 % will be used.

To carry out the comparison using field LFG data, the cumulative CH_4 generation for each cell was calculated by (i) averaging the triplicate total gas flow readings for each date of collection; (ii) multiplying the mean of the daily readings by the mean of the CH_4 percentage for that day; (iii) taking the average of the weekly readings for each month; (iv) multiplying the monthly average flow rate by the number of days in the month; and (v) summing the total monthly gas collection amounts. Dates with a zero gas flow reading were eliminated. It is also noted that LandGEM typically provides gas generation estimates on an annual basis, so the equations were entered manually to provide monthly results as necessary.

In order to optimize the CH_4 production equation from LandGEM (as presented in Equation 5-1) for the waste decay parameter k using annual waste mass placement data and monthly CH_4 generation volume, the sum of squared errors was used. Since only two to four complete years of CH_4 flow data exists, optimization had to be performed on a deciyear basis (decimal year). This required stating Equation (1) in terms of decimal year production (as presented in Equation 5-2).

$$Q_d = \frac{kL_0}{10} \sum_{i=0}^{d} M_i e^{-k \cdot \left(\frac{d-i}{10} \right)}$$

Equation 5-2

Where d is the number of deciyears since initial waste placement, M_i is the waste mass placed in deciyear i, and Q_d is the methane production for deciyear d. Estimation of the waste decay rate parameter, k, for a particular cell proceeded by minimizing the sum of squared errors of Equation 2 (as presented in Equation 5-3).

$$\sum_d \left(\frac{kL_0}{10} \sum_{i=0}^{d} M_i e^{-k \cdot \left(\frac{d-i}{10} \right)} - Q_d \right)^2$$

Equation 5-3

Where d varies over the deciyear methane data for the cell. The actual data for the minimization consisted of monthly methane observations and annual waste mass values. Therefore, the Q_d values were interpolated and the M_i values were the annual waste mass observations divided by 10, so it was assumed that waste was placed uniformly throughout a given year. A quasi-Newton method was used to minimize this function.

Table 5-5 Summary of Waste Mass Inputs for LandGEM, Mg (tons)

Year	Control Cells	Retrofit Cells	As-Built	
			Cell A	Cell B
1995		424,810 (467,287)		
1996		745,369 (819,898)		
1997		585,133 (643,640)		
1998				
1999	193,771 (213,148)			
2000	148,131 (162,944)	112,263 (123,489)		
2001	35,801 (39,381)	28,577 (31,435)		
2002	49,398 (54,338)		183,680 (202,048)	256,247 (281,872)
2003	58,456 (64,302)		100,574 (110,631)	2,188 (2,407)
2004	27,139 (29,853)		178,424 (196,267)	289,747 (318,722)
2005			56,759 (62,435)	250,641 (275,705)

5.2.1 Control Cells

Waste placement began in the Control cells in 1999; however, gas collection and measurement did not commence until 2003. As a result, only LandGEM results from 2003 onward were used for comparison to field data to estimate k. Since no hydraulic barrier exists between the subcells of the Control cells, the data from each subcell were aggregated to compare to the LandGEM prediction. In general, the cumulative methane generation for Control cells appears to follow the expected landfill gas generation rate as predicted for a typical "dry tomb" landfill scenario in LandGEM. Without accounting for gas collection inefficiencies, the optimized k value (0.043) matches up very well with the curve representative of the dry tomb case of k = 0.04 yr^{-1} as presented in Table 5-6. When assuming a gas CE of 75 percent, the transformed field data indicate a waste decay rate of 0.061 yr^{-1}, greater than the AP-42 default k value of 0.04 yr^{-1}. It is noted that the actual CE of the Control cells is not known, so the actual waste decay rate may be more or less than 0.061 yr^{-1}. It is also recognized that the time period of data collection may not necessarily be indicative of long-term LFG generation trends.

Table 5-6 Optimized Landfill Decay Constant (k) for Control Cell

L_0 = 59		**L_0 = 96**	
Collected Methane	**Generated Methane[1]**	**Collected Methane**	**Generated Methane[1]**
0.043	0.061	0.025	0.035

1.Assumed a collection efficiency of 75%

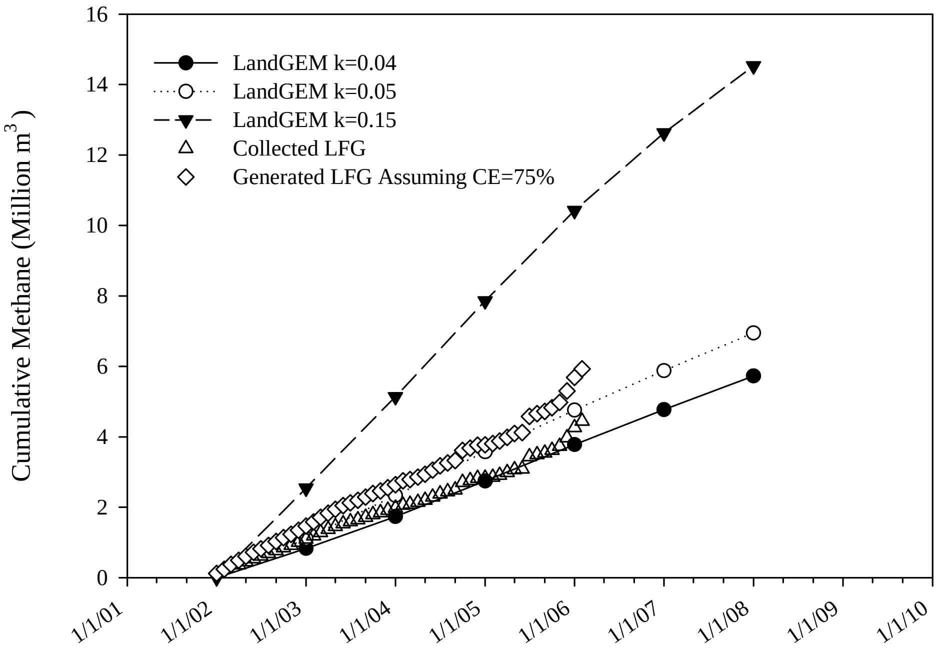

Figure 5-7 Cumulative Methane Gas Collection Data versus LandGEM-Predicted Gas Generation for the Control Cells

5.2.2 As-Built Cells

Data from As-Built cells A and B were analyzed separately since detailed waste placement data were available for each cell (see Table 5-5) and because of the hydraulic separation of these cells. LFG collection data for the As-Built cells began in April 2003. Since LandGEM provides an annual output, the output for 2003 was scaled such that it represented nine months of predicted generation (i.e., representing April 2003 to December 2003 rather than the entire year).

Cumulative methane generation predictions using LandGEM with mass input based on the available waste acceptance data (Table 5-5), beginning with a k value of 0.04 yr^{-1} (the AP-42 default for “dry tomb” landfills), and incrementally increasing up to a k value of 0.25 yr^{-1} are presented in Figures 5-8 and 5-9. A decay rate (k value) of 0.25 yr^{-1} represents the expected decay rate for wet landfills according to the U.S. EPA report “*First-Order Kinetic Gas Generation Model Parameters for Wet Landfills*” (U.S. EPA 2005). As demonstrated by the figures, the cumulative collected methane for both As-Built bioreactor landfill cells (as presented in Table 5-7) indicate a k value of between 0.15 yr^{-1} and 0.20 yr^{-1} in As-Built cells. The optimization of the decay constant k indicated that the k value for both bioreactor cells are statistically similar at 0.11 yr^{-1}. Moreover, if it is assumed that the collected gas represents 75% of the methane being

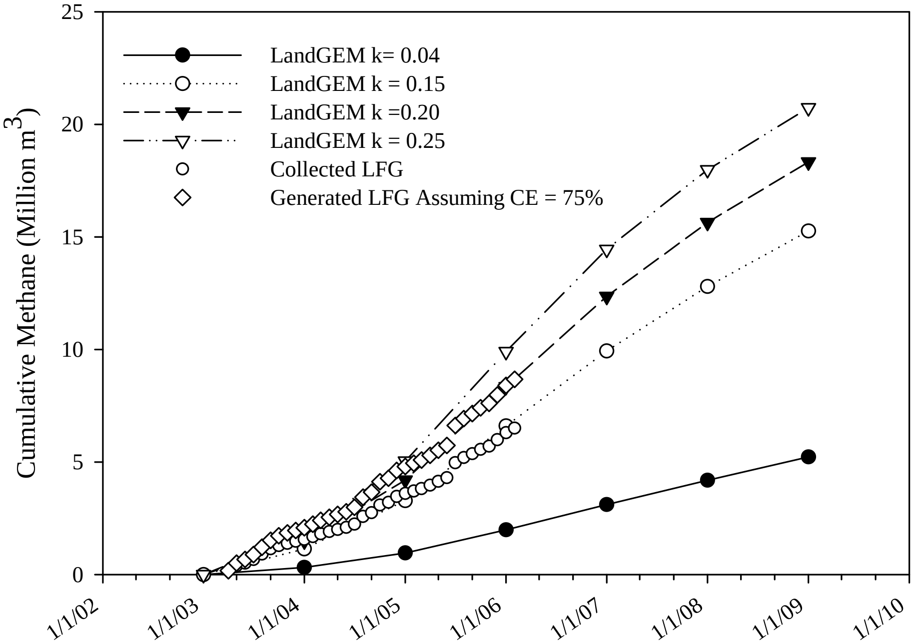

Figure 5-8 Cumulative Methane Gas Collection Data versus LandGEM-Predicted Gas Generation for As-Built Cell A

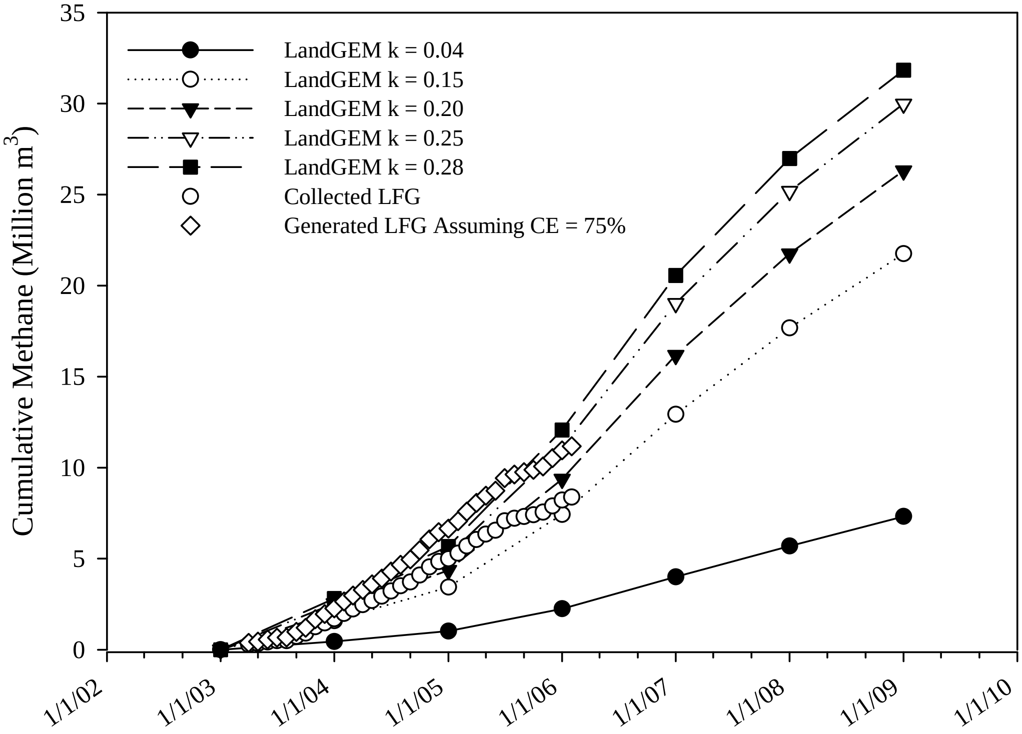

Figure 5-9 Cumulative Methane Gas Collection Data versus LandGEM-Predicted Gas Generation for As-Built Cell B

Table 5-7 Optimized Landfill Decay Constant (k) for As-Built Bioreactor Cells

Landfill Cell	L_0 = 59		L_0 = 96	
	Collected Methane	Generated Methane	Collected Methane	Generated Methane
As-built A	0.11	0.16	0.064	0.089
As-built B	0.11	0.15	0.062	0.086

generated (i.e., a CE of 75 percent), the k value for As-Built cells is optimized at a value of 0.16 yr^{-1} which falls within the range that was visually estimated before and that is statistically higher than that observed for the control cells.

These results suggest that based on gas collected at the site between 2003 and 2006, the As-Built cells appeared to generate LFG at a rate that is clearly higher than would be expected at traditional “dry tomb” landfills. As described earlier, the waste decay rate in the Control cells is approximately 0.06 yr^{-1} which is much lower than that of the As-Built cells. As illustrated in Figure 5-10, LFG generated in the early stages of the landfill’s life was significantly greater in the As-Built bioreactor cells relative to the Control and dry tomb cells.

Modeling of LFG generation rates for 50 years based on current loading rates and k of 0.16 (yr^{-1}) indicates the effectiveness of bioreactor landfills at generating methane at a faster rate relative to a “dry tomb” cells as presented in Figure 5-10. The higher LFG generation rate, especially in the early stages of landfill development, has implications for potential beneficial reuse of LFG. Furthermore, the As-Built LFG curves, shown in Figure 5-10, indicate that LFG generation declines to very low rates after approximately 25 years; this has the potential to reduce long-term concerns regarding LFG management during post-closure. These results should be viewed with caution since the developed k values are based on only 3 years worth of landfill gas collection data.

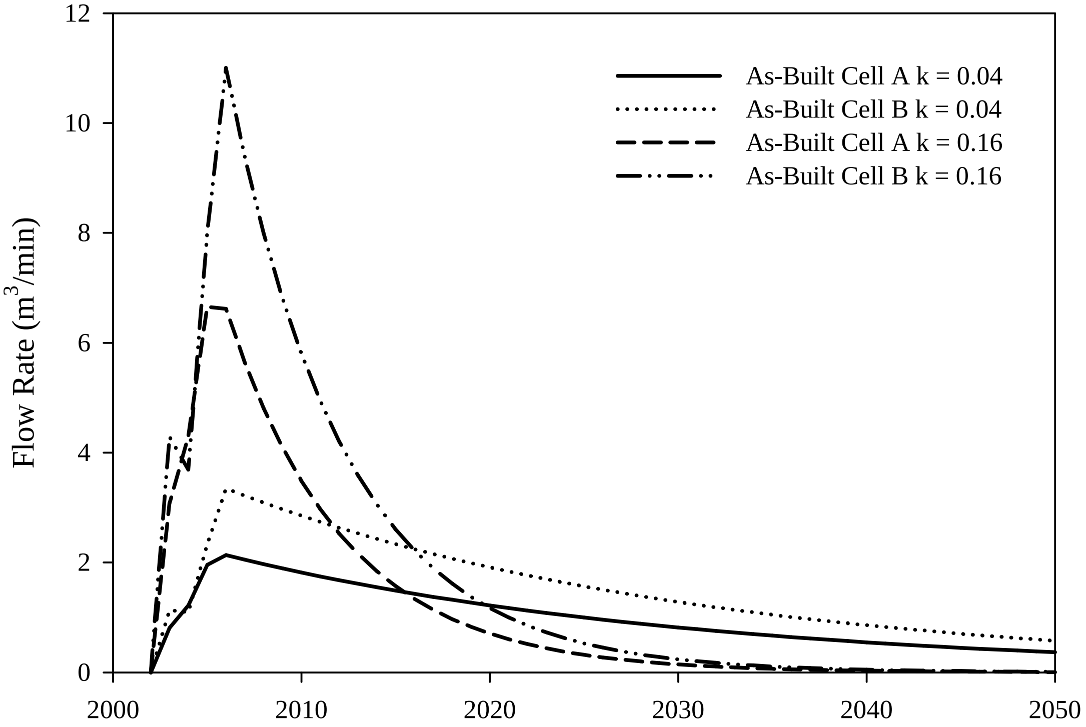

Figure 5-10 LFG Generation Rate Prediction for As-Built Cell A and B

5.2.3 Retrofit cells

Unlike the As-Built bioreactor landfill cells, the Retrofit cells were not hydraulically separated. As a result, the LFG collected from the two collection points was aggregated to calculate methane collection for further use in modeling the Retrofit unit. LFG collection started in November 2001. For LandGEM modeling of the Retrofit cells, a k for a "dry tomb" landfill case (i.e., $k = 0.04$ yr^{-1}) in addition to higher k values were explored. Results presented in Figure 5-11 show that direct field measurements of LFG generally fall just above ($k = 0.041$ yr^{-1}) the expected gas generation in "dry tomb" landfill. However, when a CE of 75% was applied, methane generation approximately matched the curve corresponding to a $k = 0.061$ yr^{-1} which is slightly higher than "dry tomb" landfill but not higher than that of the Control cell. The U.S. EPA document regarding k values for wet landfills indicated that modeled landfill sites had a k value that ranged between 0.11 and 0.3 yr^{-1}. Even with the assumption of 75 percent CE, the data for the Retrofit unit fall well below the lower bound of that range.

As discussed previously, LFG collection in the Retrofit cells exhibited erratic behavior with regard to CH_4, CO_2, and O_2 concentrations during the sampling period. It is believed that this trend can be attributed to a combination of watering out of gas wells, air leakage, air intrusion, and operator error. Upon review of Figures 5-5 and 5-6, it is noted that each figure shows LFG concentration for Retrofit cells A and B as expected for the first four months of operation (i.e., November 2001 through February 2002). Figure 5-12 depicts the average LFG collection flow rate for the Retrofit cells during the study. This figure shows that the LFG generation was highest during the first four months before starting a precipitous decline in flow for the first few months of 2002, when the installation of new vertical gas wells was stopped. As a result, it appears that the erratic behavior in terms of LFG composition began as the LFG collection rate decreased, indicating that the existing vertical gas collection wells may have been affected. It is likely that the wells filled with either the liquids that were being applied during this time period and/or with gas condensate. The magnitude of the impact on LFG CE is not known, since the determination of specific gas collection efficiency was beyond the scope of this project. Furthermore, the fluctuation of LFG flow rate beginning in

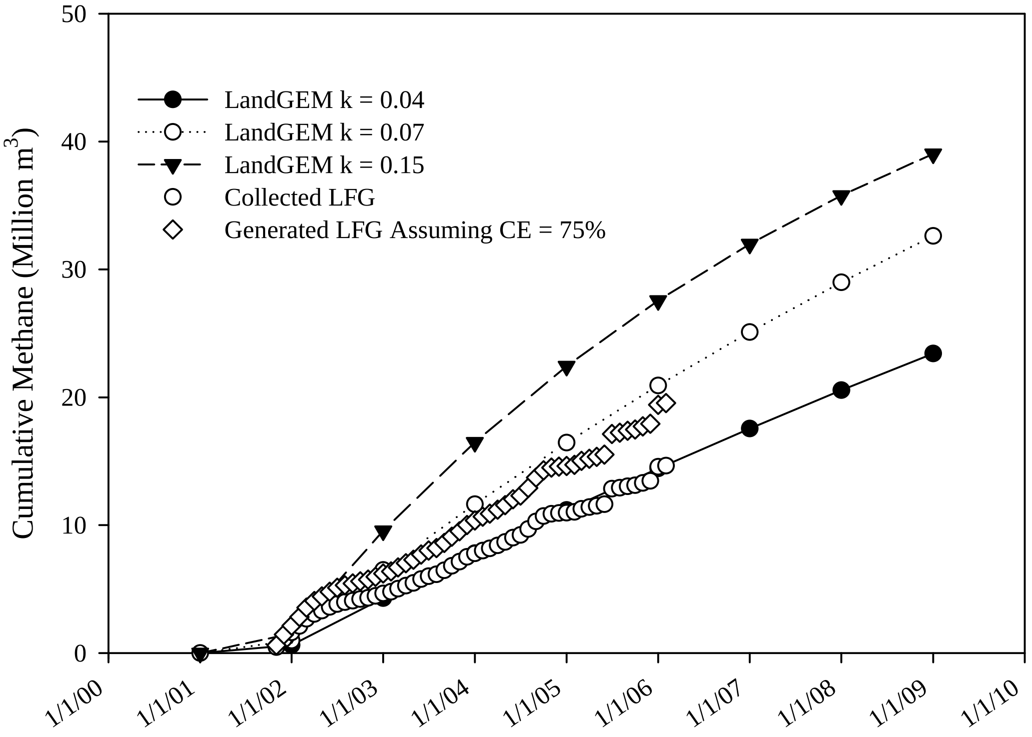

Figure 5-11 Cumulative Methane Gas Collection Data versus LandGEM-Predicted Gas Generation for the Retrofit Cells

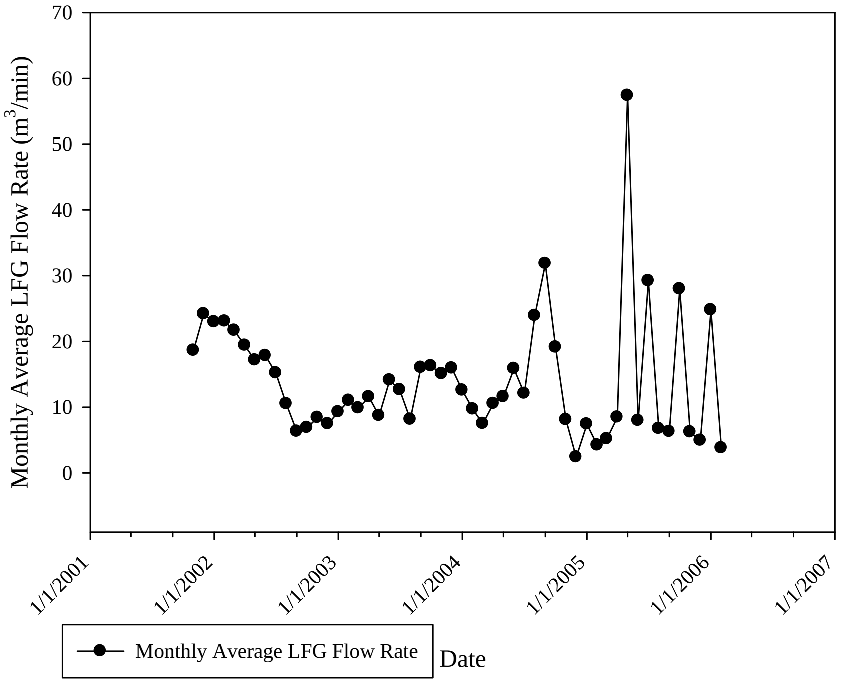

Figure 5-12 Monthly Average LFG Flow Rate for Retrofit Cells

late 2004 (see Figure 5-12) may be the result of an increase in the vacuum on the Retrofit cells. The comparison of Figures 5-5 and 5-6 to Figure 5-12 indicates that the increase in gas flow rate generally coincides with a decrease in CH_4 and an increase in O_2, indicating over-pulling on the LFG well field. Furthermore, operators for LFG well monitoring were replaced at the same time and this may have contributed to the erratic readings after that time.

Figure 5-13 compares the modeled LFG generation rate for the Retrofit unit ($k = 0.061\ yr^{-1}$) to the decomposition rate in the AP-42 default. The results indicate that the decomposition rate in the Retrofit unit was greater than the modeled LFG production based on the decomposition rate of the regulatory default value. The difference in LFG generation is not as dramatic in the Retrofit cells compared to the As-Built cells (assuming similar loading rate). It is important to note that the Retrofit Unit was not operated as a bioreactor landfill until 2001, approximately six years after initial waste placement. Based on the first-order decay LFG production model for MSW, fresher (i.e., newly placed) waste generates LFG at a greater rate than older waste. Therefore, the timing of landfill bioreactor operations and the time period of collected LFG field data (2001 to 2006) is not perfectly comparable to the Control cell. In addition, the older refuse in the Retrofit cell may have contributed to a lower decay rate.

5.3 Comparison of Field Gas Results of Control and Landfill Bioreactor Cells

A comparison of the CH_4 flow rates between the Control (i.e., dry tomb) cell and the experimental (i.e., landfill bioreactor) cells is critical in understanding the effectiveness of landfill bioreactor operations. The hypothesis is that with the greater degradation rate in bioreactor landfill cells, compared to dry tomb cells, landfill gas will be generated at a greater rate. Since waste placement and mass in the test cells varied, a direct side-by-side comparison over the entire monitoring period was not possible. Comparisons were only made in months for which gas collection data for waste of similar age was available as summarized in Table 5-8 and 5-9. The mass of waste in each cell was normalized to the mass in the Control cell as the rate and amount of CH_4 generated, over time, is proportional to the mass in the cell. The waste age, shown in Tables 5-8 and 5-9, is relative to the year of initial waste placement for each cell (e.g., a waste age of six

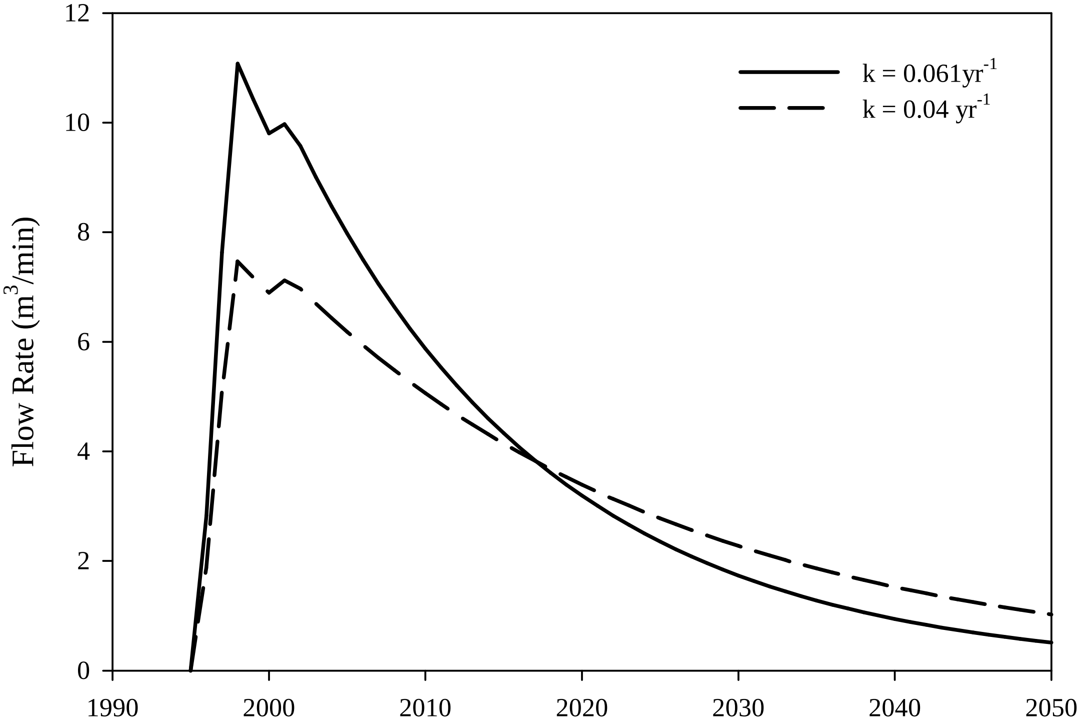

Figure 5-13 Modeled LFG Generation Rate for Waste in the Retrofit Cells

is compared in Table 5-8 since waste filling began in 1999 and 1995 for the Control and Retrofit cells, respectively). To carry out the comparison, the ratio of CH_4 generated in a bioreactor landfill cell to that generated in the Control cell on these dates was calculated and plotted as presented in Figures 5-14 and 5-15. The observation number listed in the tables corresponds to the observation number located on the x-axis of each of the figures. The dashed horizontal line at a ratio of one indicates no difference in gas generation (based on collected gas data) between the Control cells and the landfill bioreactor cells.

Figure 5-14 shows that the data for the comparison of the Control and Retrofit Unit fell below the ratio of 1.0 for the first two observations and above the line for the last two observations. As presented earlier in Chapter 3, liquid introduction into the Retrofit landfill Unit did not started until May 2001. As a result, there was not adequate time for good moisture distribution, between May and November, to see an enhancement in the LFG generation rate in the Retrofit Unit. The increasing trend in the ratio over time, observed in Figure 5-14 suggest that, with time, the Retrofit Unit was able to produce more gas. This observation is inline with the solids data results (presented in Chapter 4) that suggested that the Retrofit cells are potentially decomposing at a rate higher than the Control cells. However, as with the solids data, more data are needed to better document trends.

Because of the filling schedule, more gas observations were available for the comparison of the bioreactor landfill cells and Control cells as presented in Table 5-9. As shown in Figure 5-15, the ratios of the landfill gas generated in the bioreactor landfill cells to that generated in the Control cells were often higher than 1, suggesting that the rate of degradation was greater in the As-Built bioreactor landfill. This conclusion is further supported by the solids data (see Chapter 4) that show more rapid solids decomposition in the As-Built cells.

Table 5-8 Summary of Dates Used for Retrofit and Control Cells CH_4 Flow Comparison

Observation #	Waste Age (Yr)	Control Month	Retrofit Month
1	6	11/2005	11/2001
2		12/2005	12/2001
3	7	1/2006	1/2002
4		2/2006	2/2002

Table 5-9 Summary of Dates Used for As-Built and Control Cells CH_4 Flow Comparison

Observation #	Waste Age (yr)	Control Month	As-Built Month
1	3	1/2002	1/2005
2		2/2002	2/2005
3		3/2002	3/2005
4		4/2002	4/2005
5		5/2002	5/2005
6		6/2002	6/2005
7		7/2002	7/2005
8		8/2002	8/2005
9		9/2002	9/2005
10		10/2002	10/2005
11		11/2002	11/2005
12		12/2002	12/2005
13	4	1/2003	1/2006
14		2/2003	2/2006

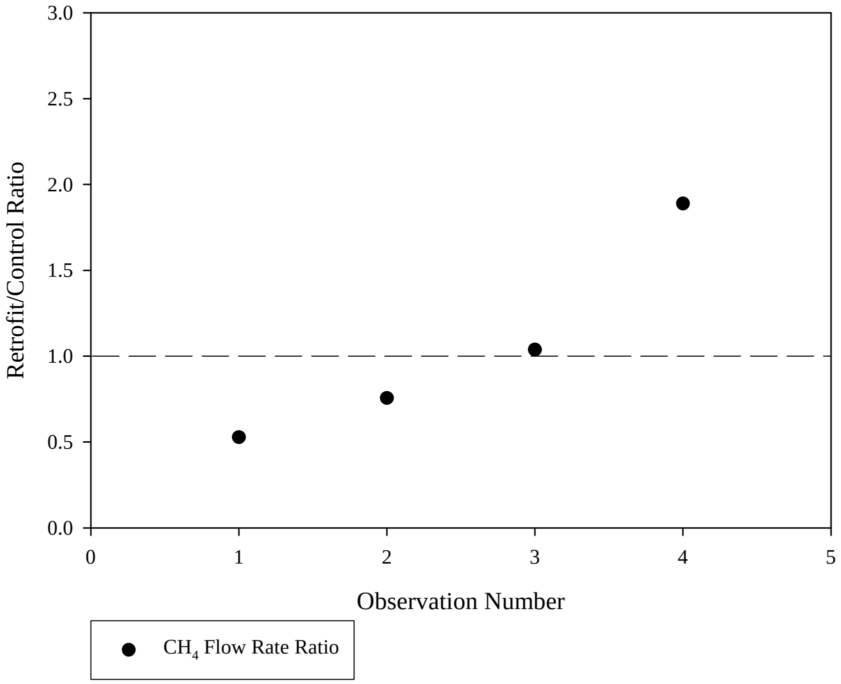

Figure 5-14 Normalized Comparison of Gas Collection in Control and Retrofit Cells

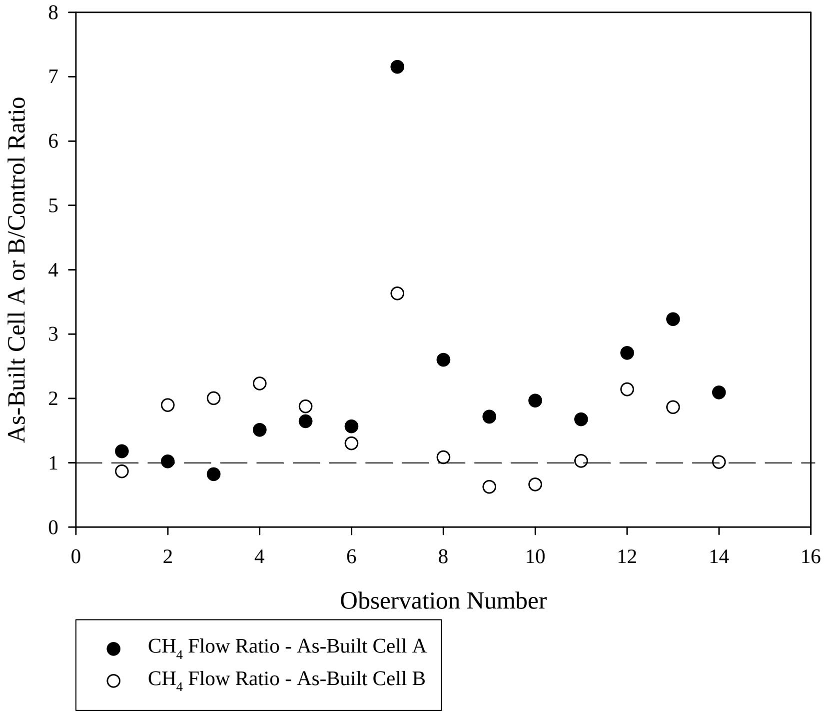

Figure 5-15 Normalized Comparison of Gas Collection in Control and As-Built Cells

5.3.1 Summary of LFG Generation

The measured LFG generation rates, the decay constant (k), and the solids data presented in the previous sections indicate that there is an increase in solid waste degradation in bioreactor landfills compared to Control cells. The enhanced LFG generation rate indicates that the majority of LFG production will occur in the early stages of landfill development (in the case of the As-Built cells in this study, within the first ten years following initial waste placement). Figure 5-16 shows the percent of LFG generated as a function of years after waste placement for the various k values estimated earlier in this section. Based on this analysis, 50% of LFG is generated within 7 years of waste placement at a k of 0.16 yr^{-1}. This trend has significant implications for potential beneficial use options for LFG at MSW landfills operated as a bioreactor during and after waste filling since the rapid LFG generation would mean more recoverable energy is available sooner. The trend further underscores the importance of having a LFG collection system in place in the early stages of landfill development for: (i) ambient emission control if a landfill is to be operated as a bioreactor and (ii) an increase in LFG collected if a beneficial use of the LFG (e.g., LFG-to-energy) is considered for the site. If a LFG collection system is not in place during the early stages of landfill development, the most LFG-productive years will be missed, resulting in greater emissions and lower cumulative LFG utilization.

These trends also have an implication for post closure care. Based on LandGEM model data presented in Figure 5-16, more than 90% of LFG is produced within 12 years after waste placement in bioreactor landfill cells as compared to less than 50% in the Control Units. Thus, if the potential for LFG generation is low (e.g., 90% of LFG has already been produced) in MSW landfills operated as bioreactors, then an argument could be made that the duration of post closure care monitoring for LFG may be reduced.

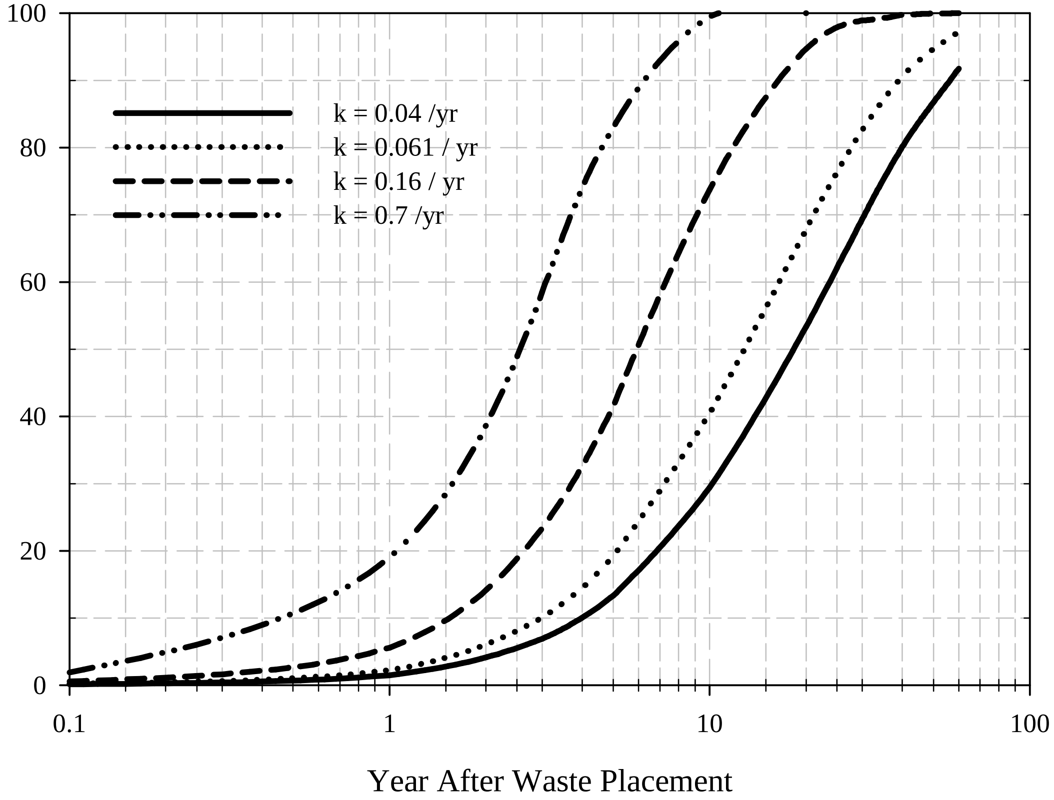

Figure 5-16 Normalized Comparison of Gas Collection in Control cells and As-Built Cells

5.4 None Methane Organic Carbon (NMOC) Concentrations in LFG

Samples for analysis of total NMOCs and a number of speciated HAPs that are a subset of NMOCs were collected for all cells on a quarterly basis and sent under chain-of-custody protocol to Severn Trent Laboratories as outlined in the QAPP presented in the First Interim Report. Summary statistics for the HAP data are provided as Appendix E. Non-detected constituents were not included in the statistical analysis represented in the tables. In evaluating the air pollutant concentrations, a correction was used to account for air infiltration. Furthermore, only constituents detected in more than 50 percent of the samples were included; these constituents were then corrected for air infiltration using the following equation from U.S. EPA's AP-42 guidance document:

$$C_p = \frac{C_{P,u}\ (1x10^6)}{C_{CH_4} + C_{CO_2}} \qquad \text{Equation 5-4}$$

Where:

Cp = Corrected concentration of pollutant P in LFG, ppmv;
$C_{P,u}$ = Uncorrected concentration of pollutant P in LFG, ppmv;
1×10^6 = Constant used to correct concentration of P to units of ppmv;
C_{CH4} = CH_4 concentration in collected gas, (ppmv); and
C_{CO2} = CO_2 concentration in collected gas, (ppmv).

Currently, little is known about the kinetics of NMOC emissions from MSW landfills, specifically as the NMOC emissions relate to waste type, waste age, and other factors. NMOCs are generated in MSW landfills from volatilization of organic compounds and, to a limited degree, by biological and chemical processes (U.S. EPA, 1998; Staley et al., 2006). The Clean Air Act (CAA) default concentration for NMOCs in MSW LFG is 4,000 ppm as hexane. This value was developed for compliance purposes, but AP-42 indicates that NMOC concentrations greater than this default concentration can exist at MSW landfills. AP-42 defaults for NMOCs are 600 ppm for MSW landfills with minimal co-disposal occurred at the site.

When considering a comparative analysis of NMOC production, the use of only NMOC concentration data from a landfill cell may be misleading. NMOC concentrations must be tied in with the LFG flow rate to evaluate production. Additionally, the mass of waste and the composition of waste would likely affect the magnitude of NMOCs produced. In this section, the analytical data (i.e., NMOC concentrations) will be tied into available LFG flow rate data to calculate the mass flow rate of NMOCs from the different cells. Only total NMOC data are analyzed in this section, since the individual compounds listed in the QAPP and analyzed in the laboratory (i.e., HAPs) are a subset of NMOCs. The data will be analyzed to present the analytical results on a unit (i.e., mass) basis. Summary statistics for total NMOCs are presented in Table 5-10.

The mean NMOC concentration (presented in Table 5-10) varied between cells. Differences between concentrations ranged from a factor of approximately 4.5 (e.g., Retrofit cells versus Control cell A) to as little as approximately 1 (e.g., As-Built cell B versus Retrofit cells). It is noted that higher NMOC concentration in a particular cell does not necessary mean higher emissions since NMOC production rate depends on the volume of LFG generated by each cell. Furthermore, the calculated NMOC production averages do not directly account for the differences in the mass of waste in the cell or waste age. Thus, a direct between-cell comparison of NMOC production is inaccurate. The aforementioned lack of accurate predictive methods of NMOC production does not allow for any meaningful conclusions to be drawn based on NMOC concentration alone. Furthermore, the differences between the cells with regard to the time of waste placement, coupled with the NMOC sampling frequency outlined in the QAPP, limits the pool of data that can be compared.

Table 5-10 NMOC Concentration for Each Sub Cell (ppm as Hexane)

Subcell	Number of Detects	Range (min-max)	Median	Mean ± Standard Deviation
Control cell A	14	383-1,608	1,146	1,060±368
Control cell B	14	450-867	633	611±117
As-Built cell A	10	97-633	458	393±177
As-Built cell B	10	85-467	233	242±100
Retrofit cell A	15	63-350	250	246±73
Retrofit cell B	14	143-383	250	237±71

5.4.1 Landfill Gas (LFG) Flow-Based NMOC Production Analysis

As noted in Chapter 3, the Control and Retrofit cells were sampled at more than one location; however, there was no hydraulic separation between the cells, and therefore the LFG flow data was combined for comparison with LandGEM. In this section, a similar approach will be used in evaluating the mass flow rate of NMOCs in the Control and Retrofit cells as was used for methane production. Since samples were taken from more than one point for NMOC analysis, the mean of the concentration at each selected date will be used to calculate the NMOC mass emission rate. Equation 5-5 depicts the approach for calculating the NMOC mass emission rate:

$$m = C_p \times Q_{LFG} \times \frac{1}{385.4} \times 86.17 \times 0.454 \times 10^{-6} \qquad \text{Equation 5-5}$$

Where:

m = mass flow rate of NMOC, kg/min;
C_p = concentration of NMOC corrected for air intrusion, ppmv as hexane;
Q_{LFG} = flow rate of LFG, scfm;
385.4 = conversion of ft^3 per lb-mol of gas at STP;
86.17 = molecular weight of hexane, lb/lb-mol;
0.454 = conversion of lb into kg; and
10^{-6} = conversion factor from ppm to volume fraction.

Since NMOC samples were collected quarterly, the monthly average flow rate corresponding to the month that the NMOC sample was collected was used in calculating the mass flow rate. These calculated NMOC production rates were plotted over time to evaluate potential temporal trends in NMOC production. Figures 5-17 through 5-20 depict the results for the Control, Retrofit, and As-Built cells A and B and demonstrate somewhat erratic behavior in NMOC production rate.

The NMOCs from the Control cells appear to increase and decrease randomly while showing an overall decreasing trend during the sample collection period. The As-Built cells also appear to fluctuate during the sample collection period. Overall, it does not appear to be a strong temporal trend for each cell. In general, the production rate for each cell falls between 0.002 and 0.035 kg/min (0.004 and 0.07 lb/min). The mean NMOC production rate that takes into account the cell's LFG flow rate for the Control, Retrofit, and As-Built A and B cells is 0.012, 0.012, 0.010, and 0.008 kg/min (0.026, 0.026, 0.022, and 0.018 lb/min), respectively.

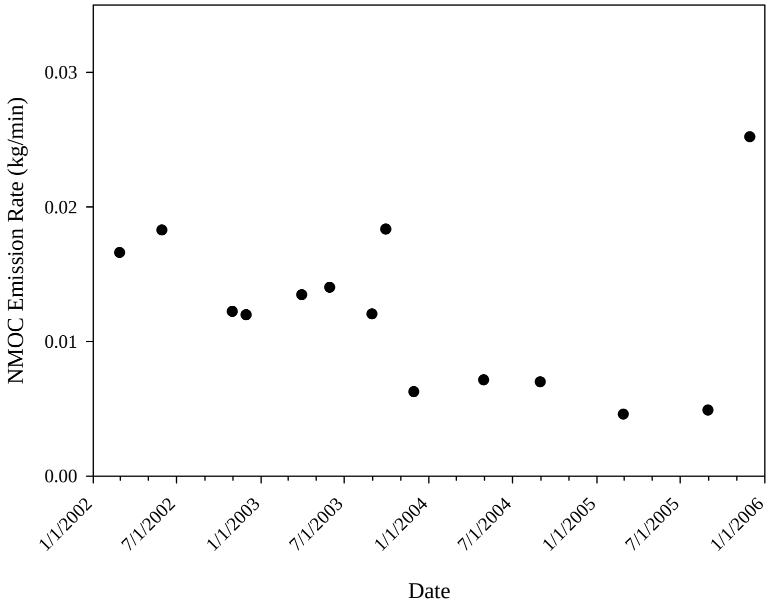

Figure 5-17 NMOC Production in the Control Cells

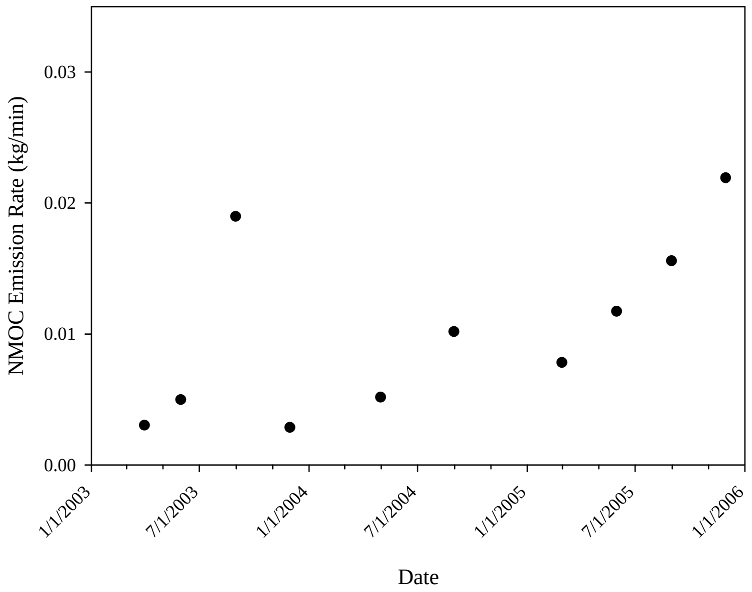

Figure 5-18 NMOC Production in As-Built Cell A

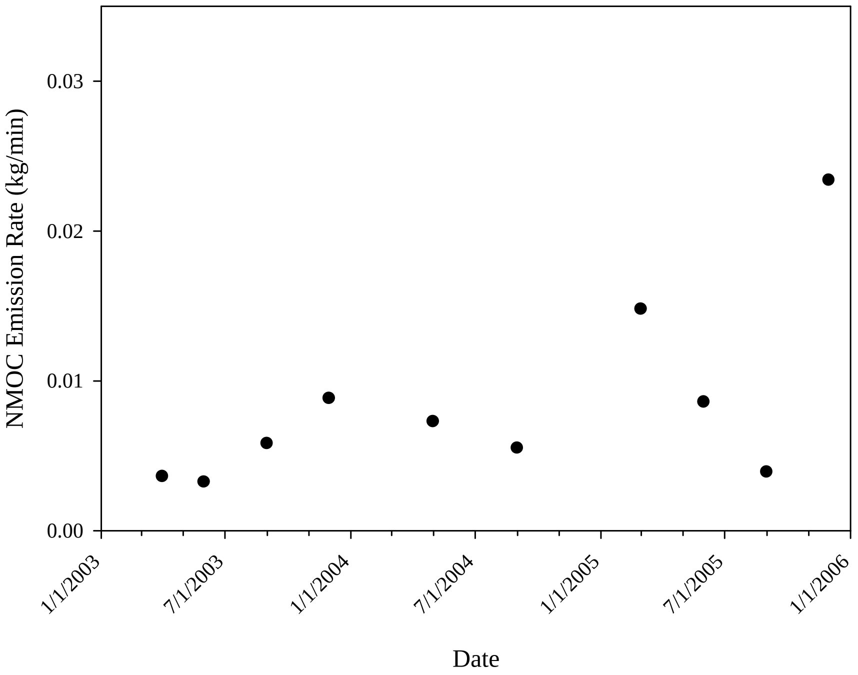

Figure 5-19 NMOC Production in As-Built Cell B

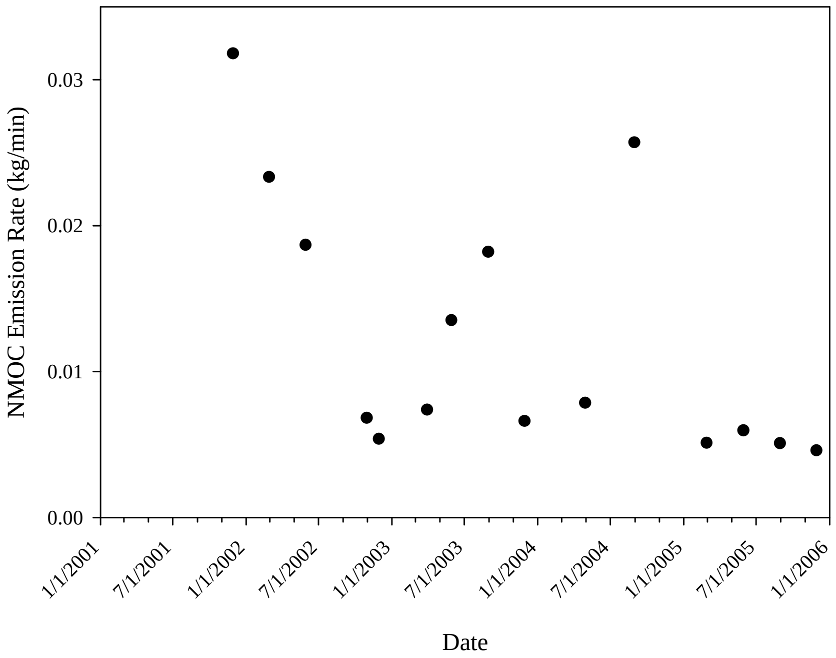

Figure 5-20 NMOC Production in the Retrofit Cells

5.4.2 *Waste Mass-Based NMOC Production Analysis*

The regulatory requirements for installing a LFG collection and control system are based on the mass flow rate of NMOCs, which is based on a tiered system. If a landfill's design capacity is 2.5 million Mg or 2.5 million m^3, a LFG collection and control system must be put in place. However, this is based on a regulatory default NMOC concentration of 4,000 ppm. If it can be demonstrated that a landfill's NMOC concentration is less than 4,000 ppm, the NMOC production rate may be modeled using the site-specific NMOC concentration and Equation 5-6.

$$M_{NMOC} = \sum_{i=1}^{n} 2kL_o M_i (e^{-kt_i})(C_{NMOC})(3.6 \times 10^{-9}) \qquad \text{Equation 5-6}$$

Where:

M_{NMOC} = Mass emission rate of NMOC (Mg/yr);
k = CH_4 generation rate constant (yr^{-1});
L_o =CH_4 generation potential (m^3/Mg);
M_i = Mass of MSW placed in year i (Mg);
t_i = age of the i^{th} section of waste (yr);
C_{NMOC} = Concentration of NMOC (ppm); and
3.6×10^{-9} = Conversion factor.

After calculating the annual mass of NMOC production, the result is compared to a regulatory threshold of 50 Mg/yr. If the calculated NMOC production exceeds this amount, then a LFG collection system must be installed in accordance with 40 CFR Subpart WWW. The site-specific NMOC concentration (i.e., C_{NMOC}) is determined by performing Tier 2 testing, which is described in Subpart WWW.

The calculation of NMOC production depicted in Equation 5-6 differs from Equation 5-5 in that it is based on the mass of waste in place as well as the parameters k and L_o of the landfill cell instead of actual LFG collection data. Equation 5-6 can be modeled in LandGEM using site-specific waste placement data and a representative NMOC concentration (based on the sampling guidelines stated in Subpart WWW). The parameters k and L_o can either be the Clean Air Act regulatory default values of 0.05 yr^{-1} and 170 m^3/Mg or determined on a site-specific basis using U.S. EPA Method 2E.

The NMOC generation rate was modeled for each cell based on available waste placement data, the regulatory default k and L_o, and the mean NMOC concentration during the study period. The mean NMOC concentration for each cell was presented in Table 5-10. Table 5-11 depicts the LandGEM-predicted NMOC production for each cell using the waste placement data presented in Table 5-5, k=0.05 yr^{-1} and L_o=170 m^3/Mg.

Typically, a demonstration of whether a landfill is above or below the 50 Mg/yr threshold is performed by summing the NMOC production rate for each landfill unit at a site for a particular year. Since this report focuses on a portion of the OLRDF, a comparison to the 50 Mg/yr threshold would be incomplete, based on available NMOC concentration data (i.e., no NMOC data were available for the cells that were not part of this study). It is not feasible to make a strong comparison of NMOC production between the Control cells and the landfill bioreactor cells using the method prescribed by the regulations (i.e., using Equation 5-6). The data presented in Table5-11 are a reflection of the waste placement data (time of waste placement and total in-place waste mass) and the NMOC concentration based on several sampling events. Since all of these data are incorporated in the LandGEM model, it is difficult to establish a cause-and-effect relationship between operation as a bioreactor landfill and NMOC production. Section 5.3, which investigated relationships between waste placement, NMOC concentration, and LFG collection data, indicated that there was no clear distinction between the NMOC productions in the Control cells versus the landfill bioreactor cells. However, it is noted that the increased waste decomposition rates discussed earlier may necessitate the early collection of LFG (regardless of predicted NMOC production) for bioreactor landfills, especially if the landfill owner/operator seeks to capture LFG for beneficial reuse (e.g., gas-to-energy).

Table 5-11 LandGEM-Predicted Mass Production Rate of NMOCs in Different Landfill Units (Mg/yr)

Year	Control Cell	Retrofit Cell	As-Built Cell A	As-Built Cell B
1995	-	0.0	-	-
1996	-	6.1	-	-
1997	-	16.6	-	-
1998	-	24.2	-	-
1999	0.0	23.0	-	-
2000	9.7	21.9	-	-
2001	16.6	22.5	-	-
2002	17.5	21.8	0.0	0.0
2003	19.1	20.7	4.3	3.7
2004	21.1	19.7	6.4	3.5
2005	21.4	18.7	10.3	7.6
2006	20.4	17.8	11.1	10.8
2007	19.4	17.0	10.6	10.3
2008	18.5	16.1	10.1	9.8
2009	17.6	15.3	9.6	9.3
2010	16.7	14.6	9.1	8.8

Note: A dash (-) indicates NMOC production was not modeled for that year since no waste was in place.

To directly compare cells, the NMOC generation rate for each cell was based on normalized mass placement and site specific L_o, k and the 95 percentile upper confidence level on the mean (as a conservative estimate of the mean) of the NMOC concentration for each cell during the study period as presented in Table 5-12. Results of the analysis are presented in Table 5-13. Although the NMOC UCL_{95} for the bioreactor cells was much lower than the Control cell (less than half), bioreactor cells produced more NMOC per year when compared to the Control cell. This observation is a direct result of the increase in LFG generation rate (higher k values) of bioreactor landfill cells. However, the amount of NMOC generated (Mg/year) drops quickly to levels below that of the Control cell within a few years of operations (7 years in the case of OLLB).

These results shed light on the importance of a LFG management system for bioreactor landfills. Bioreactor landfills are expected to emit NMOCs more rapidly than dry tomb cells. However, bioreactor landfill NMOC emissions tend to drop much quicker than dry tomb cells, thus reducing long-term concerns.

Table 5-12 LandGEM Model Input Values for NMOC Side-by-Side Analysis

Parameter	Control cell	Retrofit cell	As-Built cell A	As-Built cell B
k (year^{-1})	0.061	0.061	0.16	0.16
L_o (m^3/Mg)	59	59	59	59
NMOC UCL_{95} (ppm)	993	271	495	300

Table 5-13 LandGEM Predicted Mass Production Rate of NMOCs Emissions (Mg/yr)

Year After Waste Placement	Control Cells	Retrofit Cells	As Built Cell A	As Built Cell B
1	0	0	0	0
2	4.83	1.32	6.05	3.66
3	8.24	2.25	9.79	5.92
4	8.64	2.36	9.46	5.72
5	9.36	2.56	9.60	5.81
6	10.27	2.81	10.01	6.06
7	10.34	2.82	9.38	5.67
8	9.72	2.66	7.99	4.84
9	9.15	2.50	6.81	4.12
10	8.61	2.35	5.80	3.51
20	4.68	1.28	1.17	0.71
30	2.54	0.69	0.24	0.14
60	0.41	0.11	0.00	0.00

5.5 Methane Surface Emissions

Methane emissions were measured on using a CEC-Landtec SEM-500 field instrument. Surface concentrations were monitored around the perimeter of the collection area and along a pattern that traversed the landfill at 30 m intervals and where visual observations indicated elevated concentrations of landfill gas. Emissions were monitored and recorded separately for Unit 5 and 7. The climatic conditions and the background methane concentration up and downwind were recorded for each sampling event. Background concentrations averaged 5.82 ppm upwind and 9.97 ppm downwind for Unit 5, and 2.98 ppm upwind and 21.73 ppm downwind for Unit 7, for the period December 2001 to June 2006. Permit requirements necessitate a methane concentration greater than 500 ppm above the measured background level to be marked, adjustments made to reduce the surface emissions at that location, and the location to be reanalyzed within 10 days. If an exceedance exists on reanalysis, additional adjustments and/or cover maintenance must be performed and the location reanalyzed within 10 days. On a third exceedance, the Air Pollution Control District (APCD) must be notified, and either a new well installed within 120 days of the initial exceedance, or an alternative remedy submitted for approval to the APCD.

During the period from December 2001 to June 2006, Unit 5 recorded the following permit response actions:

- Reported twenty occasions of exceedances which were resolved within 10 days via adjustment of the gas collection system;
- Seven exceedances where additional soil cover was added; and
- Installation of one new gas collection well.

During the period from December 2001 to June 2006, Unit 7.3 recorded the following permit response actions:

- ● Reported fifteen exceedances which were resolved within 10 days via adjustment to the gas collection system;
- Fourteen exceedances where additional soil cover was added; and
- Five instances that required maintenance of leachate risers or changes to the gas collection header to resolve the issue.

During this same period, Unit 7.4 recorded the following permit response actions:

- Reported four exceedances which were resolved within 10 days via adjustment to the gas collection system;
- Four exceedances where additional cover soil was added; and
- One instance that required modification of the gas collection header to resolve the issue.

Chapter 6. Leachate Quality

This section considers the following parameters for the leachate quality analysis and the interpretation of the treatment performance in the different landfill units: temperature, pH, volatile organic acids (as acetic acid), BOD, COD, BOD/COD ratio, TOC, TKN, ammonia nitrogen (NH_3/NH_4-N), total iron, total phosphorous, total metals, VOCs, SVOCs, and chloride.

Leachate quality changes over time as a landfill matures and the waste characteristics change due to changes from waste decomposition. However, often that quality is governed by the bottom, most degraded, portion of the landfill (Kjeldsen et al., 2002). In this section, leachate quality over time (not waste age) is evaluated. As the statistical analysis of the solids samples demonstrated in Section 4.1, both waste age and sample date were found to have an equivalent impact in demonstrating trends or changes in waste characteristics (and therefore leachate characteristics). As such, an examination of leachate quality over time was deemed to be an appropriate context in which to view the data.

Trends of leachate parameters versus time were plotted for leachate parameters with detection frequencies exceeding 50 percent. Descriptive statistical summaries are presented in the analysis for each of the leachate parameters discussed below: (i) number of samples; (ii) percent detected; (iii) minimum number of samples detected; (iv) maximum number of samples detected; (v) mean and standard deviation of the detected samples; (vi) 95 percent UCL; (vii) 75th percentile; and (viii) 95th percentile. When the percentage detected was less than 100 percent, detection limits were noted in the summary statistics. Multiple linear regressions were used to quantify trends of the leachate parameters. When linear regression assumptions were not met, a qualitative assessment was utilized. Details on the quantitative and qualitative assessment of the leachate parameters are included in Appendix F.

The 95 percent confidence interval for the mean is the range of values that will contain the true mean (i.e., the average of the full statistical population of all possible data) 95 percent of the time. The 75th and 95th percentiles represent values that are less than or equal to the selected value, 75 percent and 95 percent of the values respectively.

6.1 Temperature

Leachate temperature may be an indicator of microbial activity in a landfill. However, temperature alone cannot predict the stages of waste decomposition. For example, temperature may also reflect seasonal variation and, to a lesser extent, the effectiveness of insulation provided by the landfill configuration. Anaerobic processes are favorable at mesophilic (30 to 38 ºC) and thermophilic (50 to 60 ºC) temperature ranges.

Leachate temperatures as a function of time in the Control, Retrofit, and As-Built cells are presented in Figures 6-1 through Figure 6-3, respectively. Based on the multiple regression analysis conducted, leachate temperature exhibited a statistically significant positive trend in the Control and As-Built cells. The same analysis, however, indicated that the leachate temperature in the Retrofit cell A had a statistically significant decreasing trend while Retrofit cell B did not display any trends. The detailed statistical analysis is presented in Appendix F. These trends can graphically be observed in Figures 6-1 through 6-3.

Overall leachate temperature in the As-Built cells (average 33 ºC) was higher than in Retrofit cells (average 27 ºC), and Control cells (average 22 ºC), potentially indicating a higher waste decomposition rate in the As-Built cells relative to the other treatments as a result of air and liquids injection that likely had stimulated and increased microbial activity. It is noted that a decrease in temperature of about 7 ºC was observed in Control cell A compared to Control cell B following the end of 2004. Reasons for such a change are currently under investigation and will be further discussed in later reports.

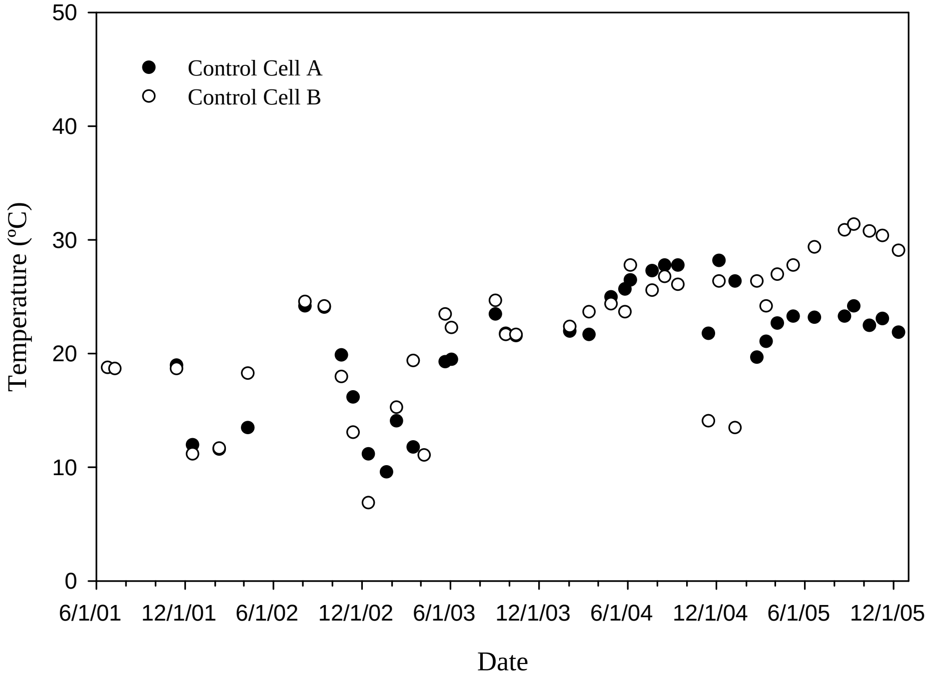

Figure 6-1 Leachate Temperature as a Function of Time in the Control Cells

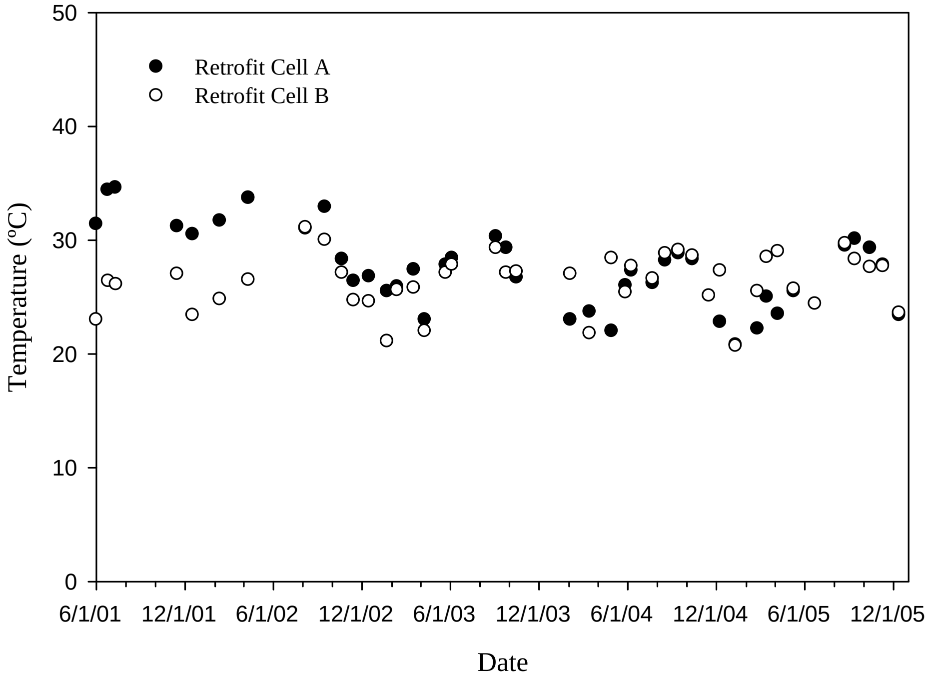

Figure 6-2 Leachate Temperature as a Function of Time in the Retrofit Cells

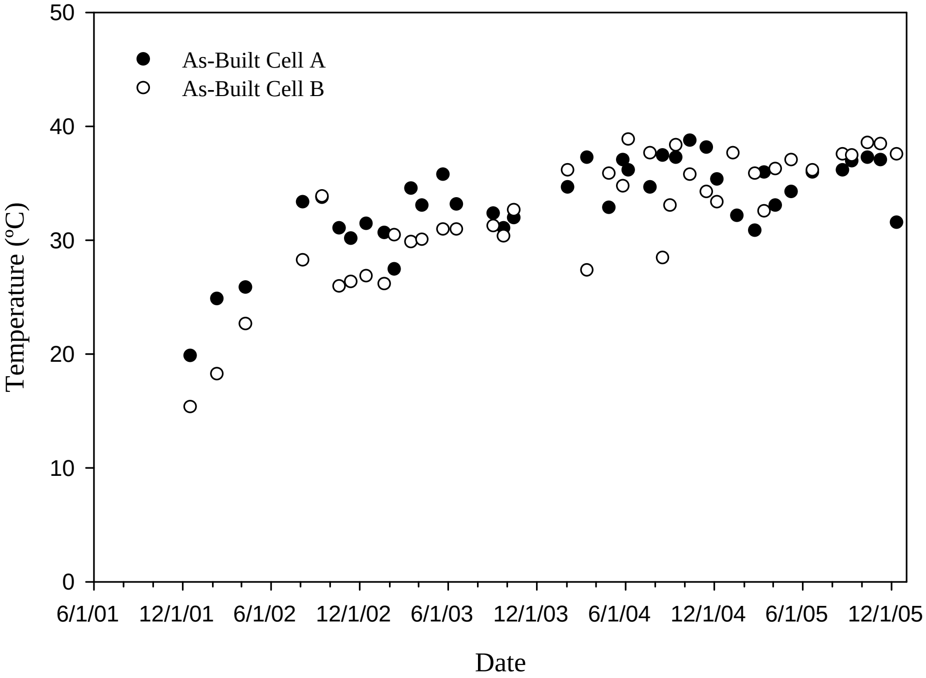

Figure 6-3 Leachate Temperature as a Function of Time in As-Built Cells

6.2 pH

The leachate pH is typically measured in landfill leachate to assist in identifying the stabilizing phase (see Chapter 2). For optimal anaerobic activity, the leachate pH is expected to range from 6.8 to 7.6 (Parkin and Owen 1986). Although the initial pH may drop, because of the production and accumulation of VOAs, it tends to rise back to the neutral range in the CH_4 fermentation phase when methanogens start consuming the VOAs. The air addition, in the As-Built cells, is expected to shorten the acid-forming phase and cause a rapid progression towards the CH_4 fermentation phase.

As with temperature, there are significant increasing pH trends (Figures 6-4 through 6-6) in the Control cells and As-Built cells, and significant decreasing trends in the Retrofit cells. The model fits are only fair as seen in the adjusted-R^2 values (See Appendix F). The pH time plots indicate that a seasonal component may be present, but when this component was added to the model, the regression fits did not improve.

Although in both the Control and As-Built cells, the pH reached neutral values by the end of 2003, a clearly defined acid forming phase was not observed. The acid forming phase occurs at the early stages of a landfill's life and may last for a relatively short period. In this study, the introduction of air may have also shortened the period of acid forming phase in the As-Built cells. Thus, in future study, measurement of leachate pH may be needed at a greater sampling frequency to identify small or sudden changes resulting from air addition. During the monitoring period, the mostly likely reason for the neutral pH values was that the characteristics of the bottom portion of well degraded solid waste influenced the overall pH of the leachate, as described earlier in this document.

A good fraction of the industrial liquid introduced into the As-Built bioreactor Cells was carbonated beverage waste which tends to be acidic in nature. Based on the leachate pH values, the addition of these types of liquids did not result in a decrease of the measured leachate pH in the As-Built bioreactor landfill cells. A sudden drop in pH to about 5.2 was observed in As-Built cell B during September 2004. This, however, was not observed in As-Built cell A, and so the limited and short-period drop in leachate pH could not be attributed to the addition of beverage waste. Once again it is noted that a decrease in pH of about 0.4 was observed in Control cell A relative to Control cell B following the end of 2004. This decrease was consistent with trends of other parameters.

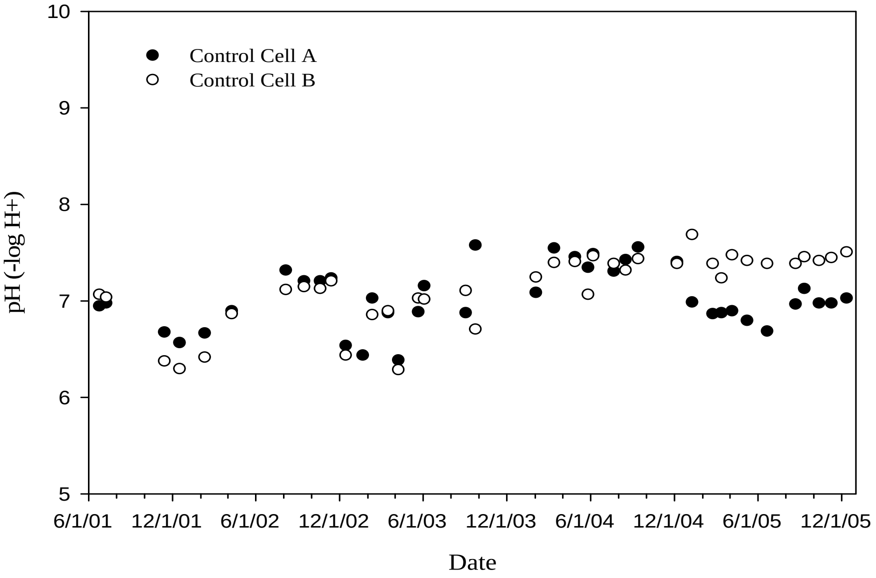

Figure 6-4 Leachate pH as a Function of Time in the Control Cells

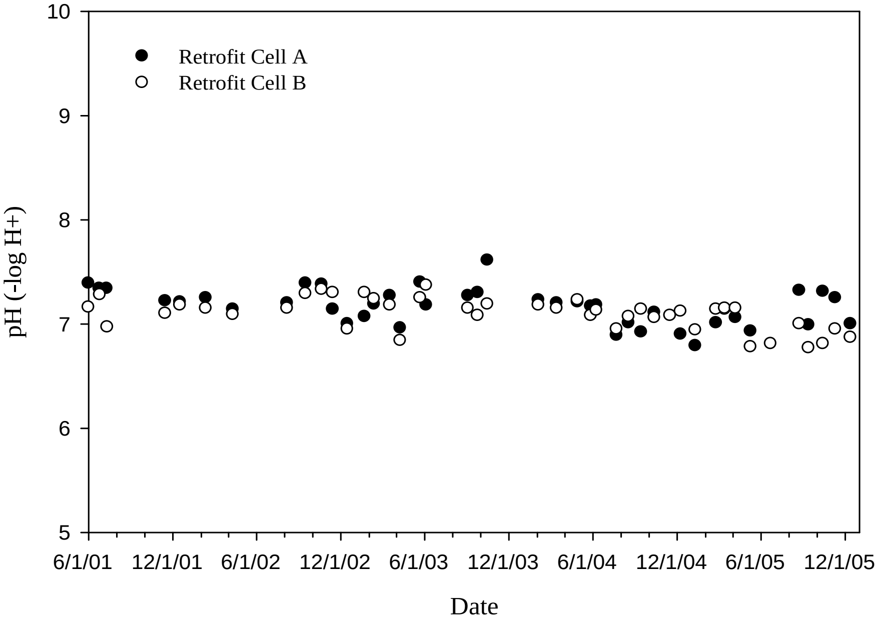

Figure 6-5 Leachate pH as a Function of Time in the Retrofit Cells

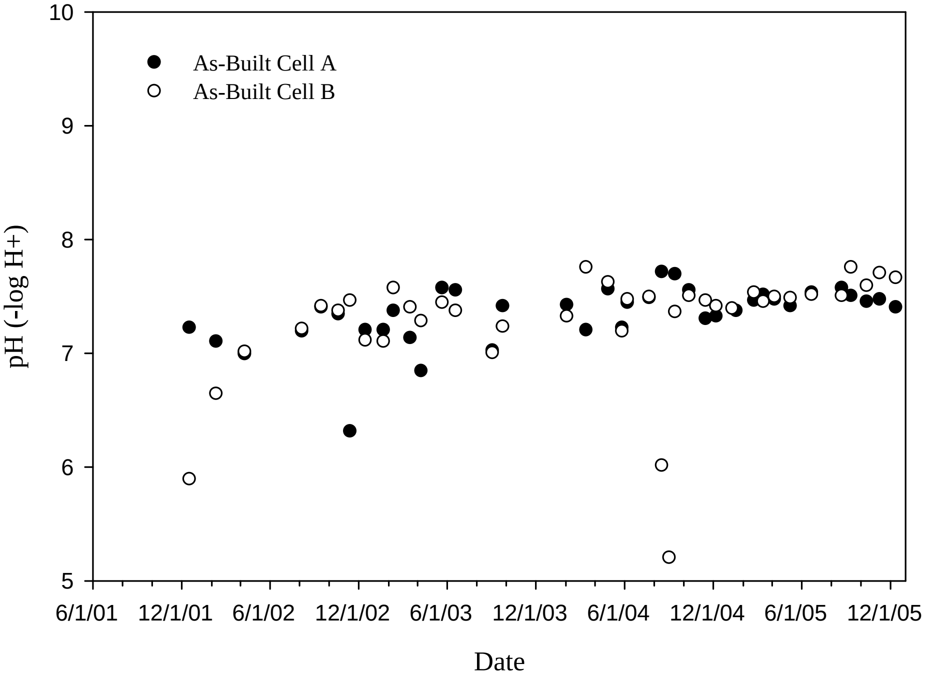

Figure 6-6 Leachate pH as a Function of Time in the As-Built Cells

6.3 Volatile Organic Acids (VOAs)

The production and accumulation of VOAs is an indicator of the acid formation phase of a landfill. The concentration of VOAs decreases over time as these acids are consumed by methanogens in the CH_4 fermentation phase. At this phase, pH is expected to increase and to stabilize around neutral values. VOAs measured in the leachate included: acetic acid, butyric acid, formic acid, lactic acid, propionic acid, and pyruvic acid. For the purposes of this report, rather than reporting the concentration of each VOA by itself, the total VOAs concentrations were calculated as acetic acid using the following equation:

$$[\text{Total VOAs}] = [\text{Acetic}] + 60 \times \left(\frac{[\text{Butyric}]}{88} + \frac{[\text{Lactic}]}{90} + \frac{[\text{Pyruvic}]}{110} + \frac{[\text{Propionic}]}{74} \right) \qquad \text{Equation 6-1}$$

where:
numerals indicate the molecular weight of each compound in grams;
brackets indicate concentration in mg/L; and
total VOAs are expressed in mg/L as acetic acid.

Of the VOAs examined in the leachate, only acetic and propionic acids were detected above their respective detection limit at sufficient frequencies. Because of the large percentage of non-detects, statistical analysis and comparisons were rather difficult to conduct. Leachate VOA concentration as a function of time in the Control and As-Built cells are presented in Figure 6-7 and Figure 6-8, respectively. VOAs in the Retrofit cells were detected at a relatively low frequency, thus will not be graphically presented in this section. VOAs concentrations exhibited a spike in the leachate of the Control cells in late 2003. Since then, with a few exceptions, concentrations of VOAs in these cells remained below 100 mg/L during the monitoring period suggesting that the CH_4 fermentation phase in the Control cells had already started. This observation is further supported by the leachate pH measured in the Control cells,

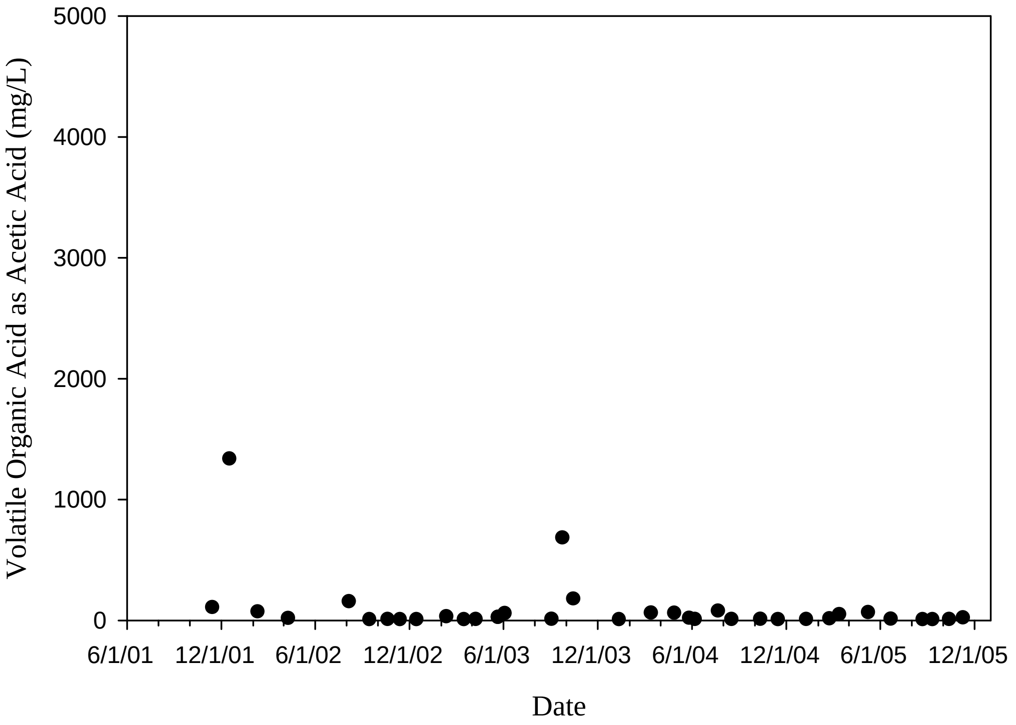

Figure 6-7 Volatile Organic Acids as a Function of Time in Control Cell B

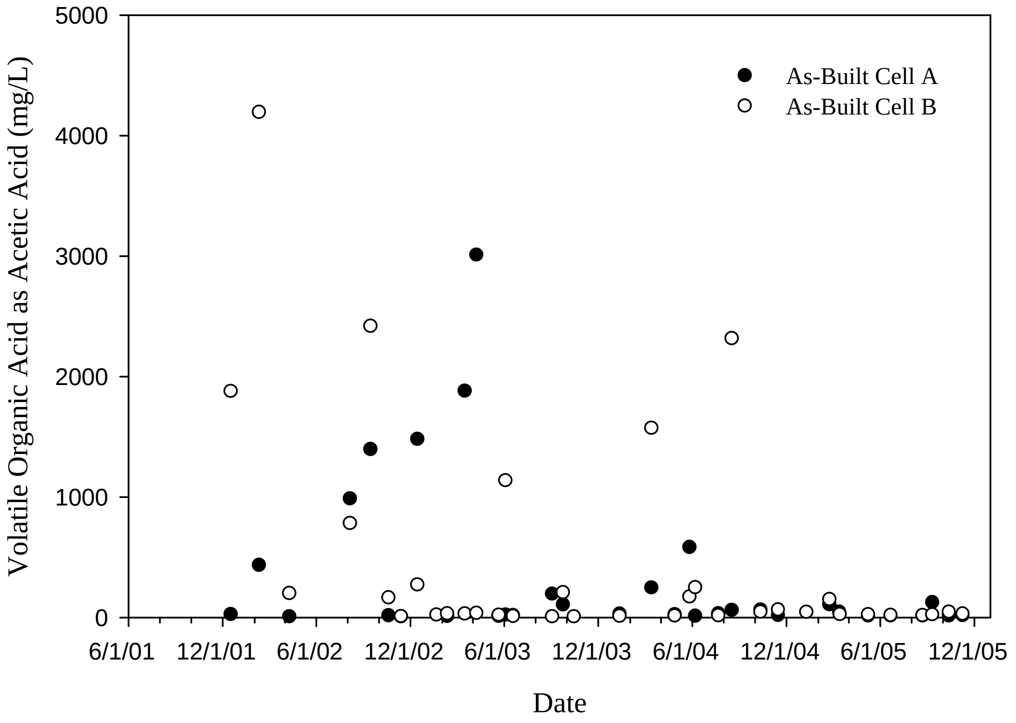

Figure 6-8 Volatile Organic Acid as a Function of Time in the As-Built Cells

which is consistent with on-going waste decomposition in the CH_4 fermentation phase. For the As-Built cells, concentrations of VOAs were relatively high with a large degree of variability from approximately 4,000 mg/L prior to mid 2004 before stabilizing below 100 mg/L at a later time. This correlated well with leachate pH increasing to reach a neutral value following the end of 2003 in the As-Built cells. It is particularly interesting to recognize that the As-Built cells generated high volumes of LFG, as was presented in Chapter 5, even during times with high VOA concentration in the leachate. The existence of this phase “accelerated methane phase” suggests that for bioreactor landfills, because of the increase in the degradation rate, it is possible to have high VOA concentration as the methane generation starts. Compared to Control cells, higher concentrations of VOAs (about five-fold) were observed in leachate from As-Built cells until mid 2004.

6.4 Total Organic Carbon (TOC)

TOC includes a variety of organic compounds, including humic and fulvic acids, VOAs, and carbohydrates. TOC measurement was not included as a leachate monitoring parameter until early 2004. A statistical summary of the TOC measurements in the leachate of the landfill units is presented in Appendix F. Leachate TOC concentrations as a function of time in the Control, Retrofit, and As-Built cells are presented in Figures 6-9 through 6-11, respectively.

Statistically, the TOC concentrations in the leachate showed no apparent trends in any of the treatment cells. The addition of beverage waste to the As-Built cells was likely responsible for the higher TOC concentrations (about three-fold) observed in this unit as compared to the Control and Retrofit cells. TOC measurements increased from about 800 to 1,500 mg/L in the As-Built cells while it ranged from 500 to 800 mg/L in the Control cells. Higher TOC concentrations could also have been caused by an increase in the rate of waste decomposition in the As-Built cells, which may have resulted in higher concentrations of VOAs, as discussed earlier. TOC concentrations in the Retrofit cells were lower compared to the other two treatment units and appeared to be stable ranging from 200 to 500 mg/L, which is again consistent with a stable phase of CH_4 production. A decrease in TOC concentration of about 600 mg/L was observed in Control cell A following the end of 2004.

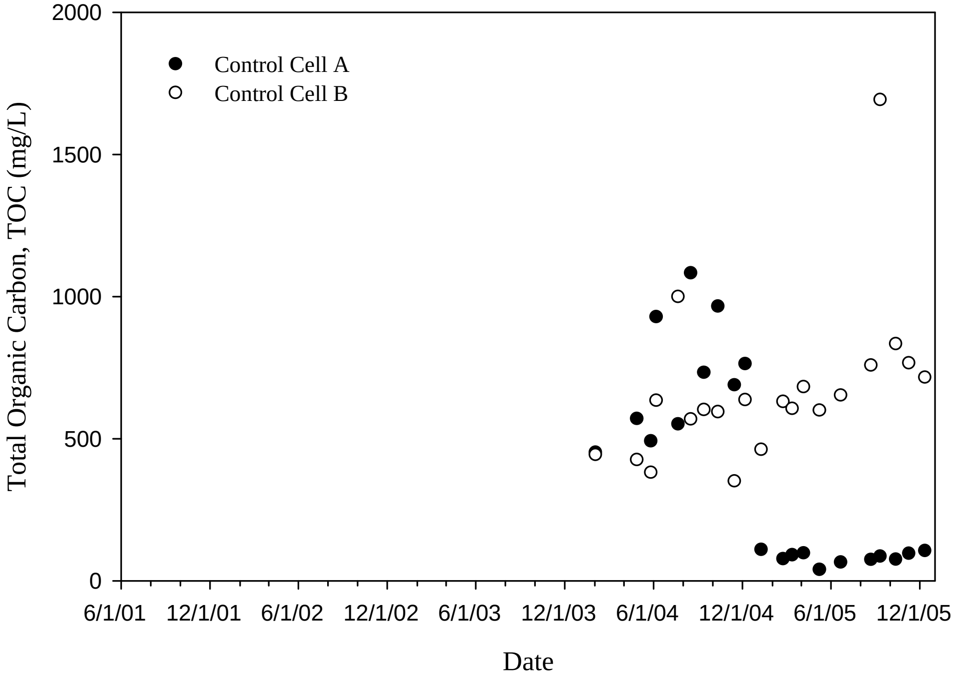

Figure 6-9 Total Organic Carbon as a Function of Time in the Control Cells

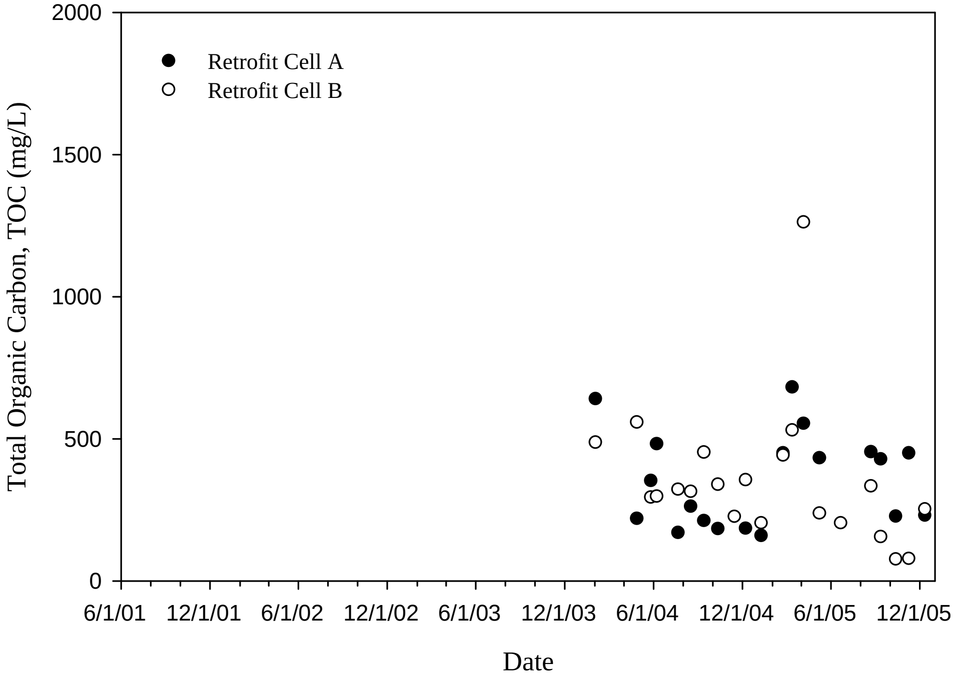

Figure 6-10 Total Organic Carbon as a Function of Time in the Retrofit Cells

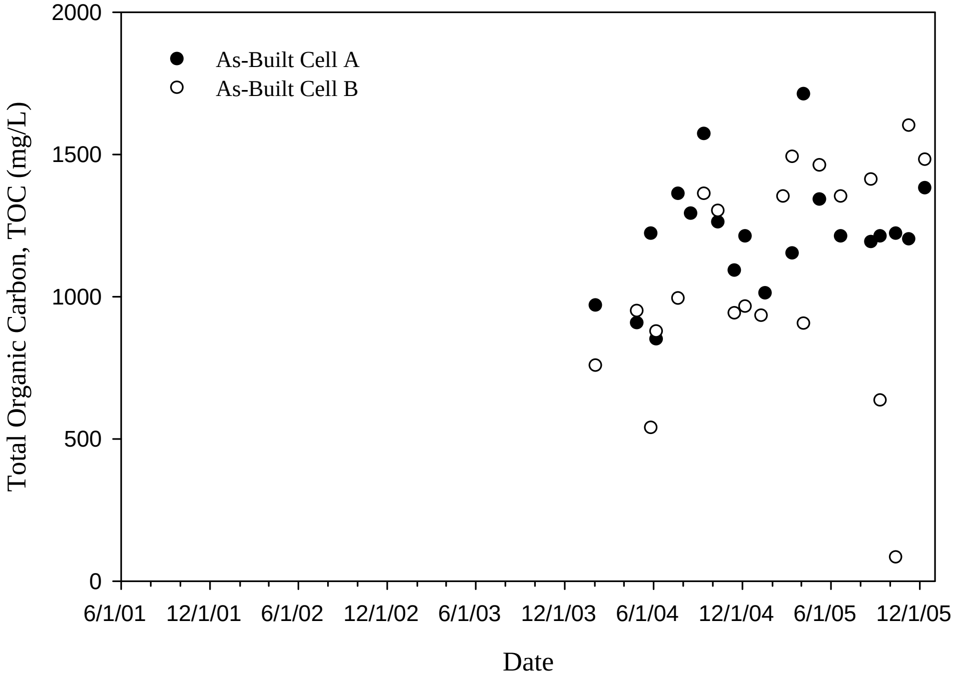

Figure 6-11 Total Organic Carbon as a Function of Time in the As-Built Cells

6.5 Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD)

BOD is generally higher in younger leachate and it decreases more rapidly than COD over time. COD includes the recalcitrant organic compounds (e.g., high molecular weight compounds as well as synthetics). Consequently, as waste ages, the ratio between BOD and COD decreases (i.e., more COD in relation to BOD). Leachate generated from waste with relatively low biodegradability was reported to have a BOD/COD ratio lower than 0.5 (Christensen et al. 2001, Reinhart and Alyousfi 1996).

A statistical summary of the BOD and COD measurements in the leachate of the different landfill units is presented in appendix F. Leachate BOD, COD, and BOD/COD ratios as a function of time in the Control, Retrofit, and As-Built cells are presented in Figures 6-12 through Figure 6-20, respectively.

BOD concentrations showed an increasing trend in the Control cells and a decreasing trend in the Retrofit and As-Built cells. Leachate from the As-Built cells exhibited BOD concentrations that were substantially higher (about five-fold) than in the Control and Retrofit cells. This could be a consequence of the high BOD in the beverage waste added to the As-Built cells. Retrofit cells displayed lower concentrations of BOD than both Control and As-Built cells, which is indicative of the more mature waste in the Retrofit cells. BOD concentrations in the Control cells ranged from 20 to 1,000 mg/L. The BOD concentration in the Retrofit cells was typically below 200 mg/L. BOD concentrations in the As-Built cells ranged from 300 to 10,000 mg/L prior to early 2004 before stabilizing at about 250 mg/L.

COD concentrations showed an increasing trend in the Control cells, a decreasing trend in the Retrofit cells and no apparent trend in the As-Built cells. Similar to BOD concentrations, the highest COD concentrations were found in the leachate from As-Built cells, followed by the Control cells and the Retrofit cells. COD concentration in the Control cells was typically below 1,000 mg/L prior to September 2003 before increasing to about 2,000 mg/L. COD concentration in the Retrofit cells decreased from about 2,000 to 1,000 mg/L during the monitoring period. COD concentration in the As-Built cells increased from about 2,000 to 5,000 mg/L during the monitoring period.

The BOD/COD ratios are comparable between the As-Built and Control cells as they both appear to show a decreasing trend early on with a more stable ratio as the waste ages. The BOD/COD ratio in leachate from the As-Built cells dropped below 0.5 at the end of 2003, almost two years after initiating landfill bioreactor activities. Similarly, the BOD/COD ratio in the Control cells dropped below 0.5 after June 2002, almost four years after initial waste placement. These results indicate that the As-Built cells exhibited a more rapid rate of decomposition relative to the Control cells. The BOD/COD ratio in both the As-Built and Control cells reached about 0.1 in December 2005. The BOD/COD ratio in Retrofit cells generally remained constant throughout the monitoring period. The ratio ranged from 0.05 to 0.08, which is indicative of mature leachate generated from less degradable (i.e., more mature) waste. Similar to the other parameters previously discussed, there is a clear difference between Control cell A and Control cell B following the end of 2004 with respect to BOD and COD. Control cell A has distinctly lower concentrations of BOD and COD compared to Control cell B.

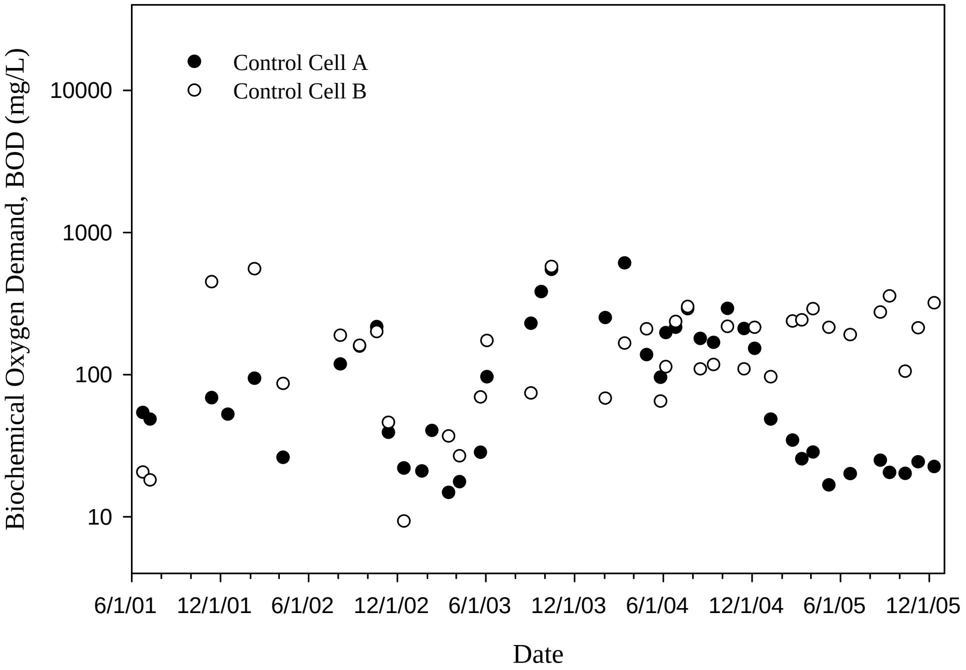

Figure 6-12 Biochemical Oxygen Demand as a Function of Time in the Control Cells

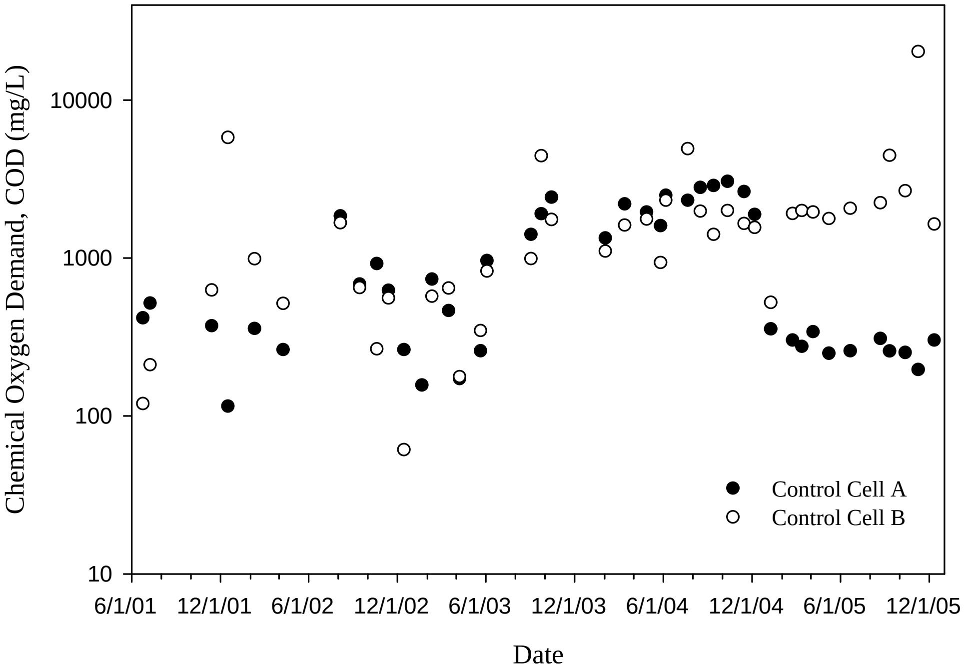

Figure 6-13 Chemical Oxygen Demand as a Function of Time in the Control Cells

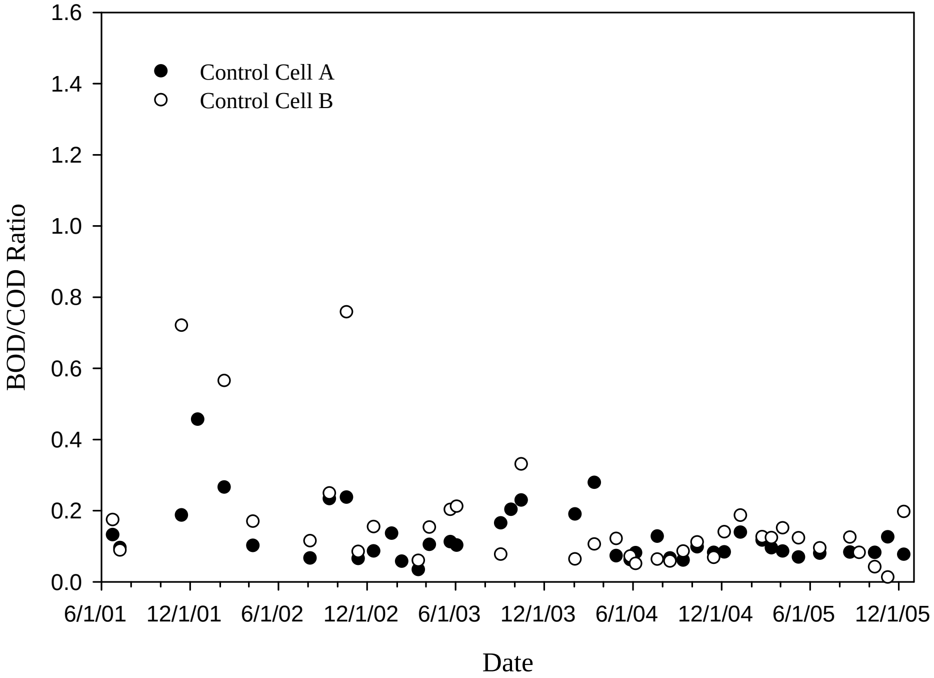

Figure 6-14 BOD/COD Ratio as a Function of Time in the Control Cells

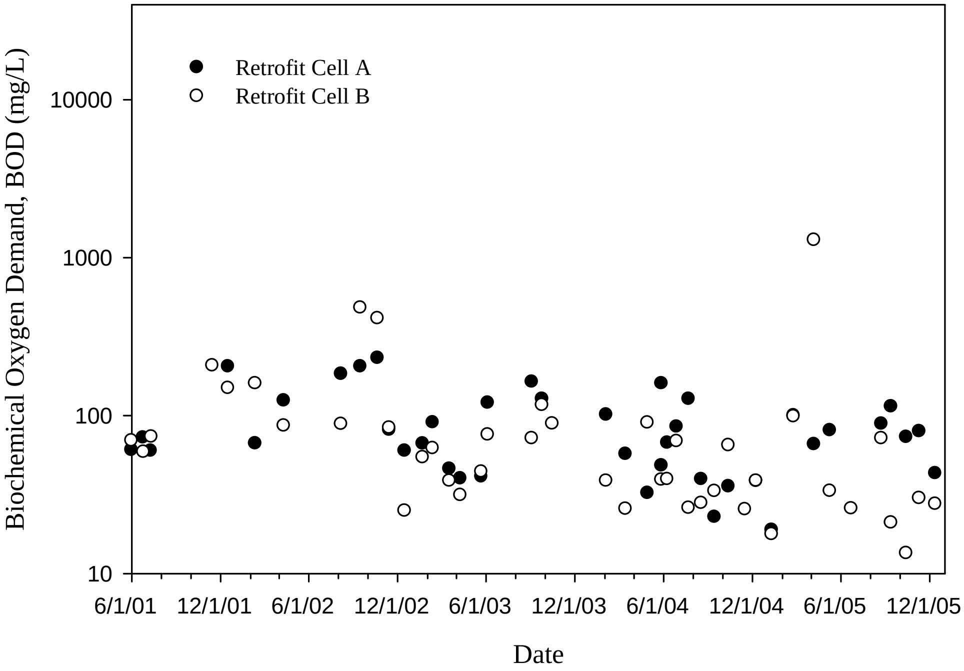

Figure 6-15 Biochemical Oxygen Demand as a Function of Time in the Retrofit Cells

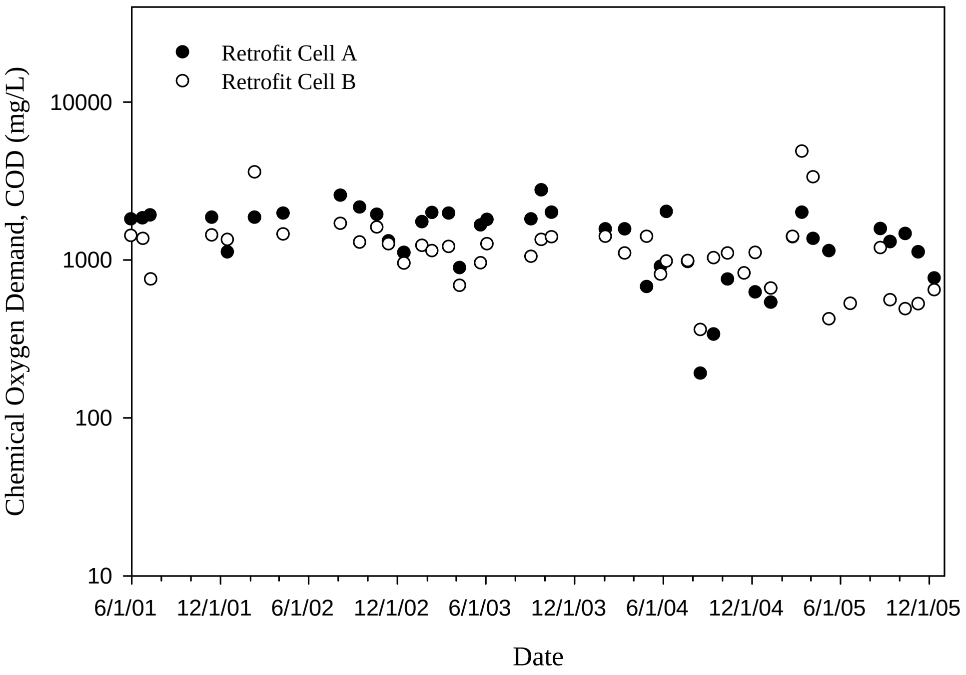

Figure 6-16 Chemical Oxygen Demand as a Function of Time in the Retrofit Cells

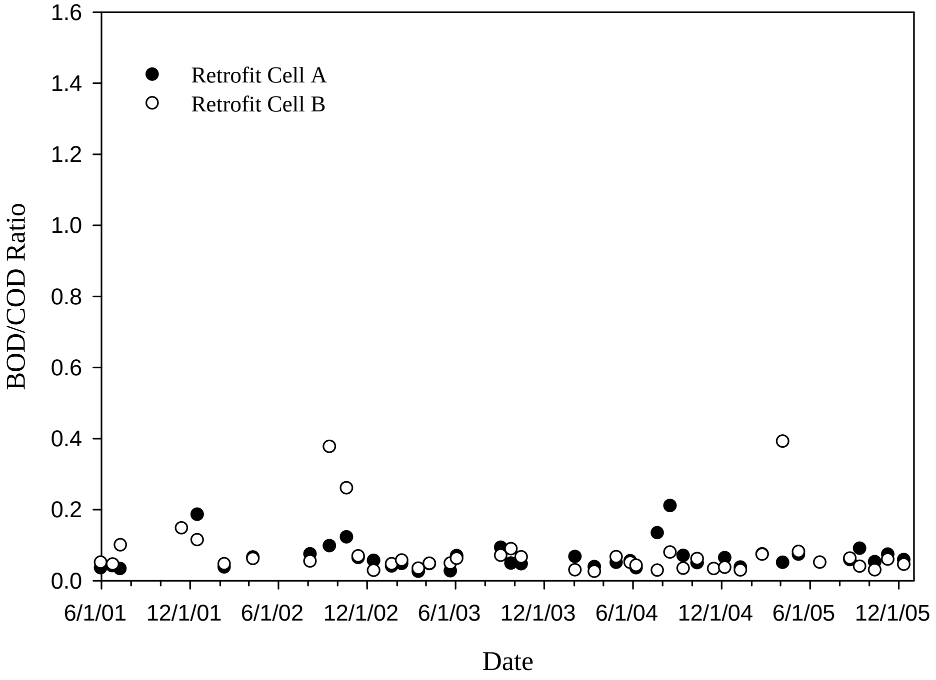

Figure 6-17 BOD/COD Ratio as a Function of Time in the Retrofit Cells

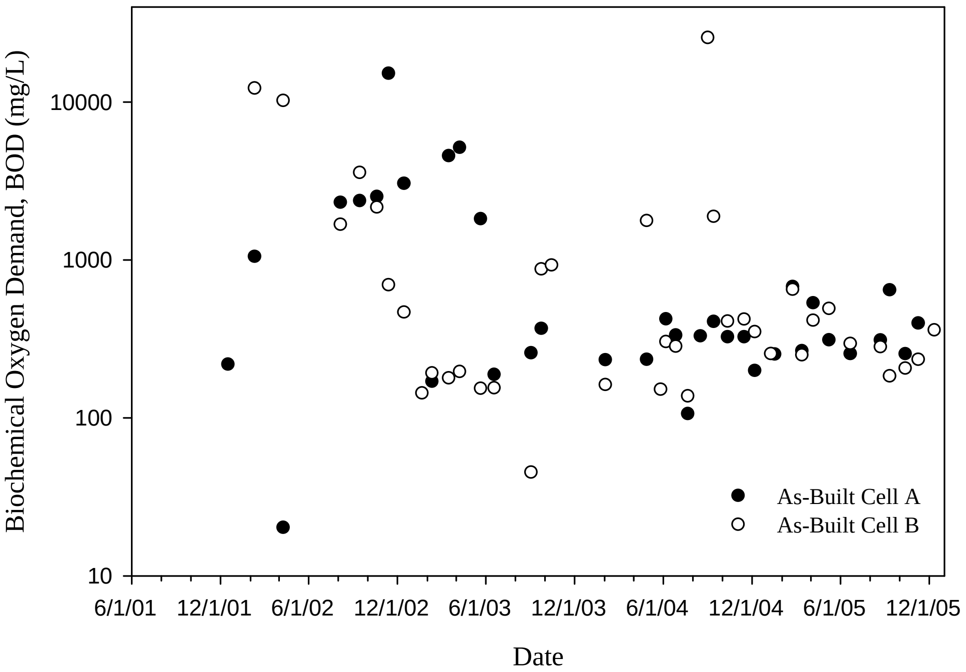

Figure 6-18 Biochemical Oxygen Demand as a Function of Time in the As-Built Cells

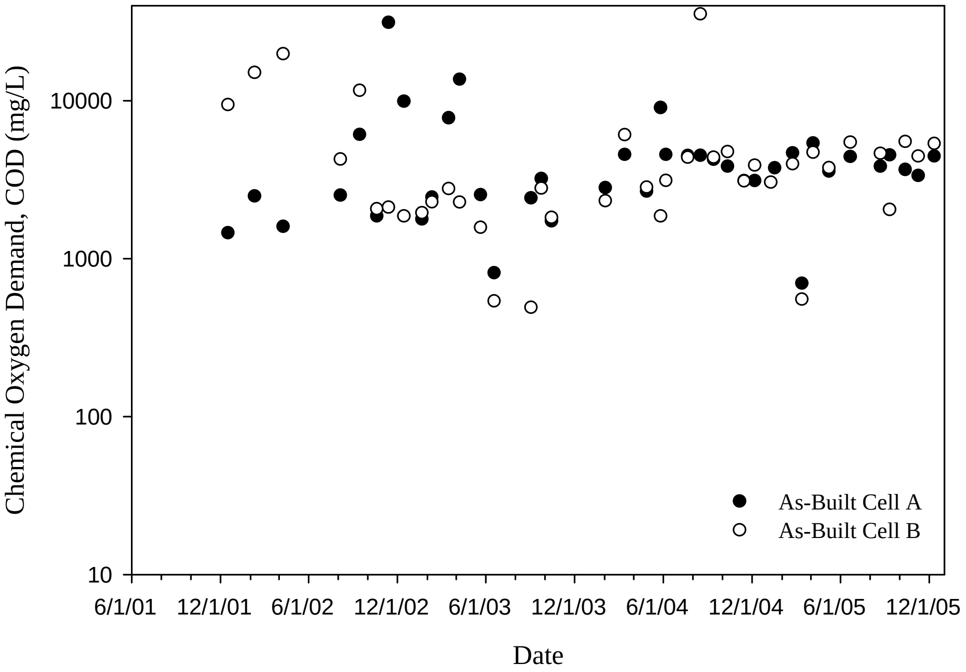

Figure 6-19 Chemical Oxygen Demand as a Function of Time in the As-Built Cells

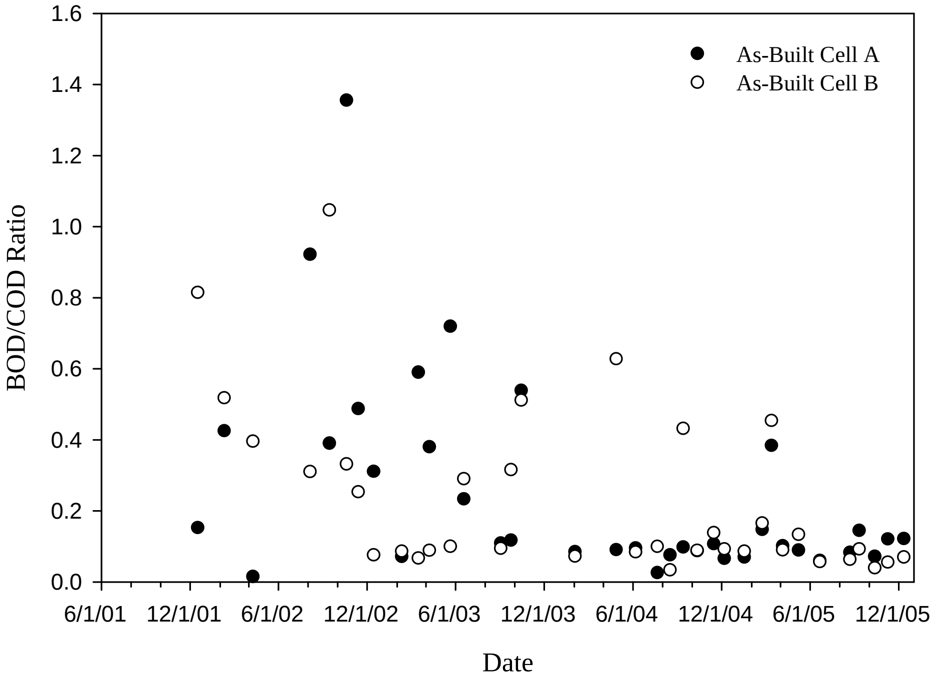

Figure 6-20 BOD/COD Ratio as a Function of Time in the As-Built Cells

6.6 Nitrogen Content

TKN is the sum of organic nitrogen plus ammonia. Ammonia concentrations should not be higher than TKN concentrations, since they are a subset of TKN. Ammonia is the reduced, inorganic form of nitrogen and is formed as a result of the release of organic nitrogen in waste. The conversion of organic nitrogen to ammonia is called ammonification. As waste degrades, ammonia concentrations in leachate generally increase as the nitrogen-bearing compounds in waste (e.g., proteins, amino acids, etc.) mineralize (i.e., become ammonified). As leachate matures, most of the organic nitrogen is mineralized and TKN is (almost) equivalent to ammonia. The conversion of ammonia to nitrate (nitrification) under aerobic conditions produces nitrite as a short-lived intermediary. Due to the anaerobic nature of leachate, nitrite and nitrate are generally not detected. However, it is noted that the Retrofit cells were injected with nitrified leachate as an additional source of liquids, which could lead to the detection of these compounds in the leachate. Furthermore, the As-Built cells were injected with air, which would be expected to facilitate nitrification and therefore increase the detection of nitrate in the leachate.

A statistical summary of the nitrogen content in the leachate of the different landfill units is presented in appendix F. It is noted that nitrate was not detected at a frequency greater than 50 percent in any of the landfill units. Nitrite was detected at greater than 50 percent frequency in the As-Built cells, but not in the Retrofit or Control cells. This was likely caused by the introduction of air into the waste in the As-Built cells. However, while nitrate also briefly spiked in the As-Built cells, it was detected at lower frequencies than nitrite, potentially indicating incomplete nitrification. Furthermore, this effect occurred over a brief period that quickly disappeared as conditions returned to anaerobic. Leachate nitrogen content (TKN and ammonia) as a function of time in the Control, Retrofit, and As-Built cells, is presented in Figures 6-21 through 6-26.

Ammonia concentration trends often reflect those of TKN. TKN concentration trends in the As-Built cells and Control cell B were similar and showed an increasing trend. TKN concentrations increased from about 250 mg/L to 1,500 mg/L and from about 100 mg/L to 1,500 mg/L in the Control cell B and As-Built cells during the study period, respectively. An increase in TKN concentrations may be an indicator of additional waste degradation in the Control and As-Built cells. TKN concentrations showed a decreasing trend in Retrofit cell A and no trend in Retrofit cell B. Ammonia concentrations showed a significantly decreasing trend in the Retrofit cells. A decrease in TKN concentrations of about 1,200 mg/L was observed in Control cell A following the end of 2004. The As-Built cells and Control cell B exhibited an increasing trend of ammonia with a similar magnitude as TKN. Ammonia concentrations increased from about 250 mg/L to 1,800 mg/L and from about 500 mg/L to 1,800 mg/L in Control cell B and the As-Built cells, respectively. A decrease in ammonia concentrations of about 1,200 mg/L was observed in Control cell A following the end of 2004, which is consistent with the decrease in TKN concentrations.

The Retrofit cells were injected with nitrified leachate and exhibited decreasing trends of TKN and ammonia concentrations. The decrease in ammonia concentrations was likely related to the nitrification process where ammonia in leachate was converted into nitrate, which counteracted the build-up of ammonia concentrations in leachate from the Retrofit cells. However, no spike in nitrate (or nitrite) concentrations was observed in these cells as a consequence of the additional liquids injection. This could be expected given the strongly anaerobic nature of leachate in these cells and the relatively low volume of nitrified leachate introduced as compared to generated leachate. It was expected that denitrification (therefore an increase in N_2 gas) of the nitrified leachate upon injection would occur; however changes in N_2 gas concentration in the Retrofit cells appeared to be intermittent and short-lived, which may be indicative of changes in N_2 concentration that were caused by operational issues (e.g., over-pulling on the gas well field and watering out of gas wells) rather than a result of denitrification. The results discussed above are again consistent with the more stable and mature waste in the Retrofit cells. TKN concentrations in the Retrofit cells gradually decreased from about 1,000 mg/L to stabilize around 500 mg/L. It is expected that the TKN concentrations in the Retrofit cells will remain at this level for decades, since research using leaching tests on MSW has shown that the nitrogen content in leachate will be substantial for centuries (Christensen et al. 2001). The Retrofit cells display a decreasing trend in ammonia concentrations from about 1,500 mg/L to 500 mg/L; these concentrations are generally lower compared to the Control and As-Built cells, indicating more stable concentrations, which is indicative of a more mature and stable waste.

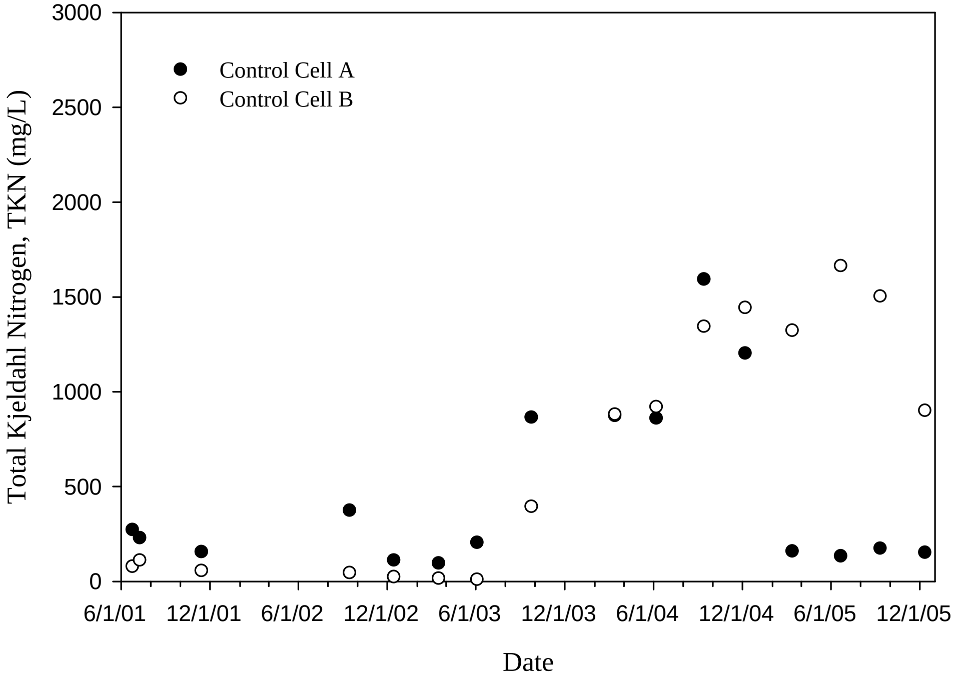

Figure 6-21 Total Kjeldahl Nitrogen as a Function of Time in the Control Cells

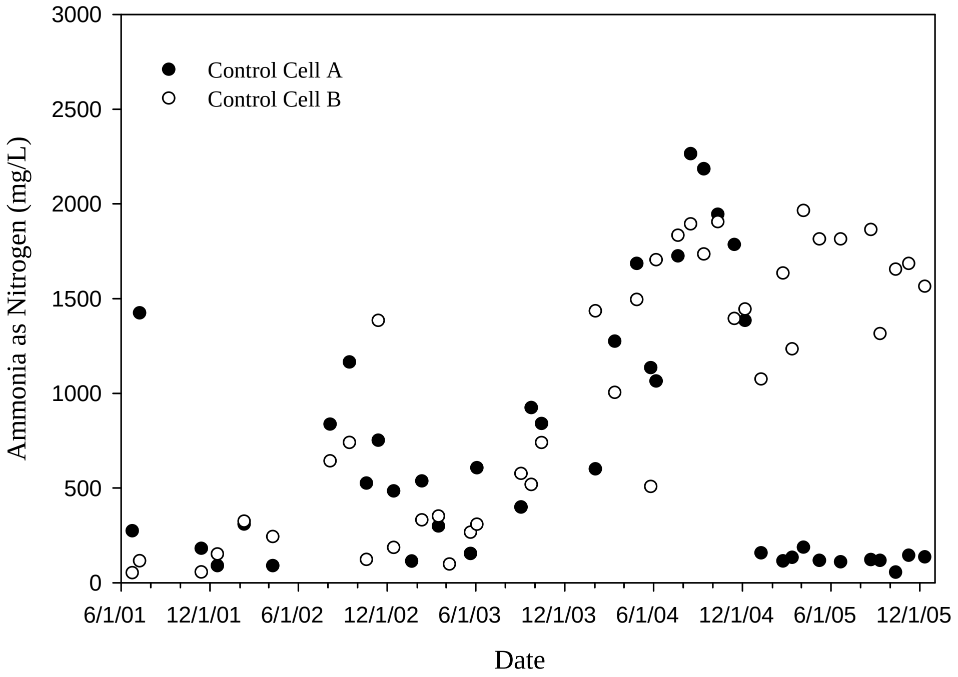

Figure 6-22 Ammonia as Nitrogen as a Function of Time in the Control Cells

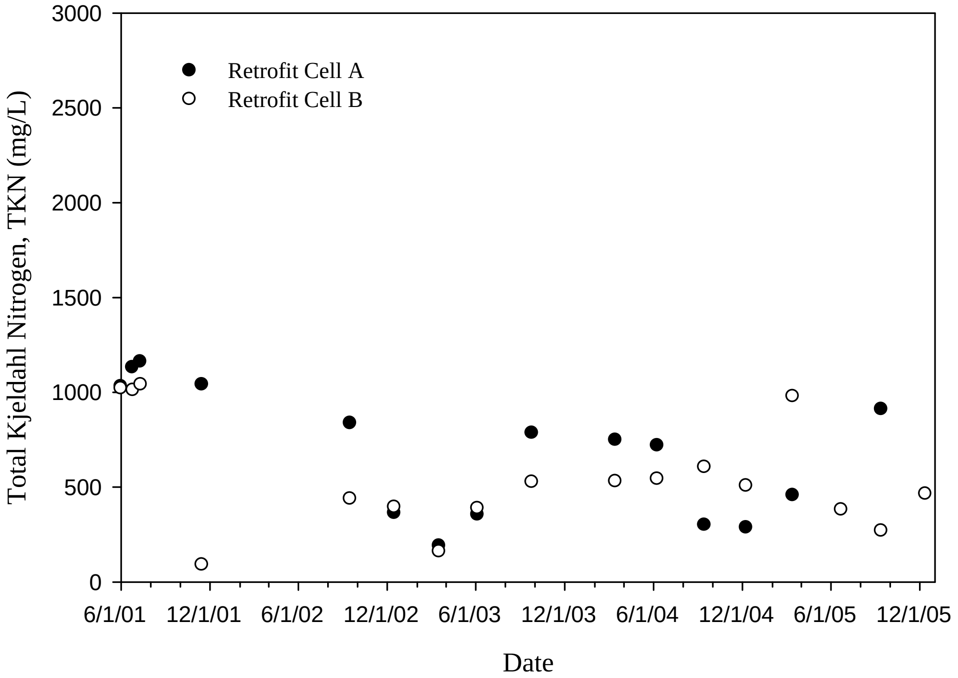

Figure 6-23 Total Kjeldahl Nitrogen as a Function of Time in the Retrofit Cells

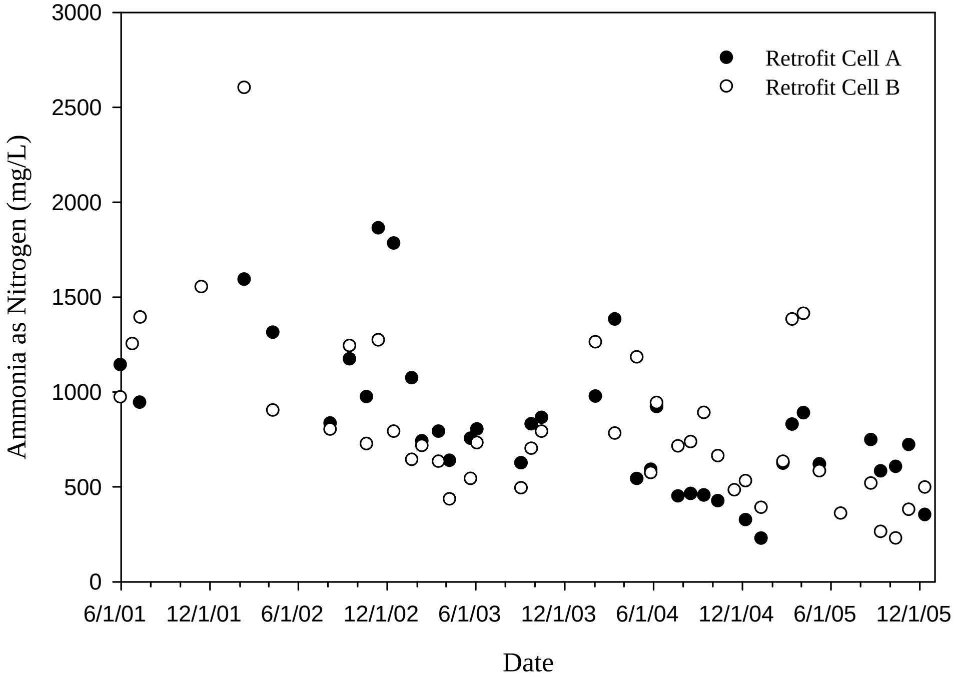

Figure 6-24 Ammonia as Nitrogen as a Function of Time in the Retrofit Cells

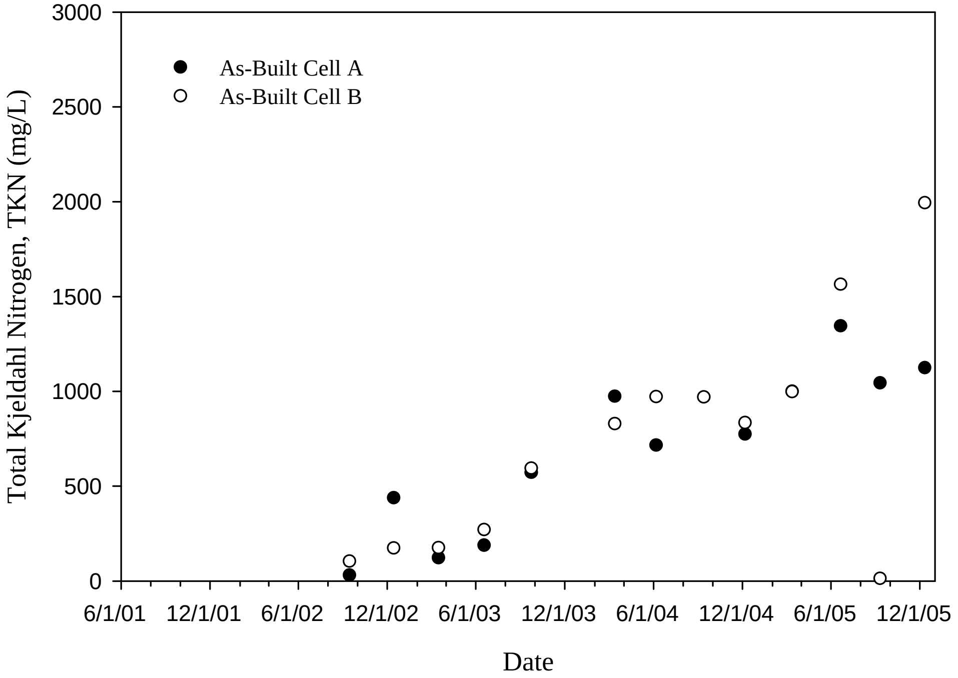

Figure 6-25 Total Kjeldahl Nitrogen as a Function of Time in the As-Built Cells

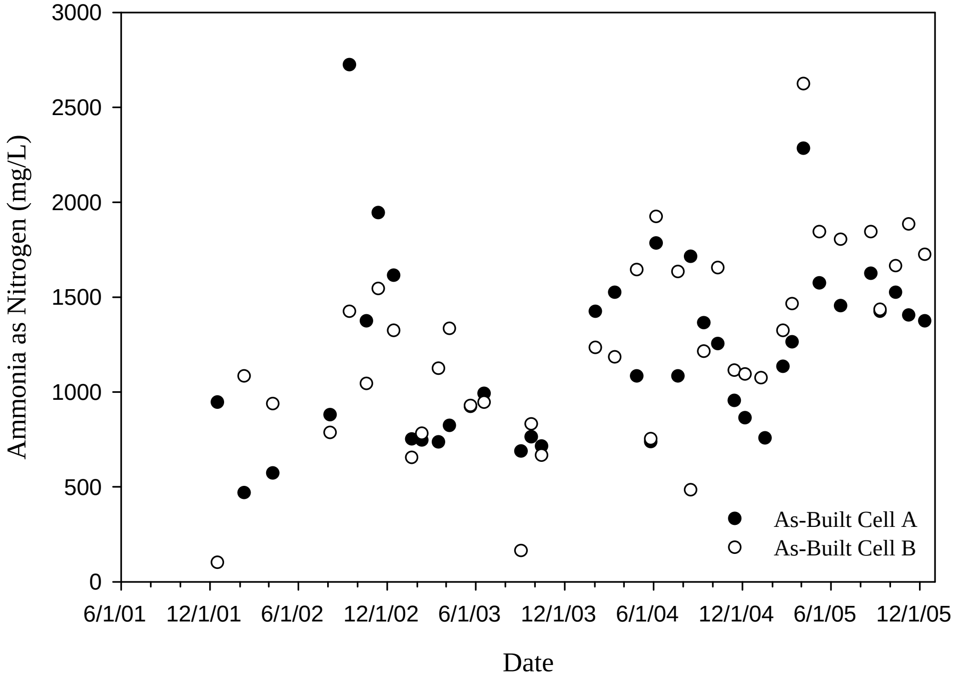

Figure 6-26 Ammonia as Nitrogen as a Function of Time in the As-Built Cells

6.7 Metals

Addition of industrial liquids into the As-Built cells may have caused an increase in the heavy metals content of the leachate. Paint and ink waste made up about 11 percent of the total liquids added to the As-Built cells. Metals that are typically constituents of paint and ink waste include arsenic, barium, cadmium, chromium, mercury, selenium and silver. Elevated concentrations of trace heavy metals in wastewater streams have been reported to retard or inhibit biological processes (U.S. EPA 1987). In general, aerobic processes are more sensitive to elevated trace metal concentrations compared to anaerobic processes, and inhibition of biological processes (and therefore waste degradation) in MSW landfills, as a consequence of elevated trace metal concentrations, is very unlikely since metals concentrations are well below the ranges reported to inhibit biological processes (U.S. EPA 1987). Trace metal concentrations are generally low in leachate from MSW landfills and are not very useful leachate parameters for a geochemical evaluation. Iron concentrations, on the other hand, are generally substantial in leachate and may be more useful as a monitoring parameter. Under anaerobic conditions, it is expected that more iron gets mobilized since the reduced form of iron (Fe^{2+}) is more soluble than the oxidized form (Fe^{3+}), which precipitates out as oxides and hydroxides.

A statistical summary of leachate metals, as presented in Appendix F, show that trace metal concentrations generally do not appear to exhibit a trend. However, it is noted that aluminum, cadmium, copper, and lead were observed at greater frequency and concentration in the As-Built cells compared to the other landfill units. This may have been caused by the injection of industrial liquids containing paint waste and ink waste into those cells. Arsenic and chromium were detected at 100 percent frequency in both the Retrofit and As-Built cells. Arsenic concentrations appeared to be slightly higher in leachate from the Retrofit cells. Arsenic is more mobile under anaerobic conditions since it is present in its more mobile (and more toxic) trivalent state (As^{3+}) compared to its pentavalent oxidation state (As^{5+}). Conversely, chromium concentrations appeared to be higher in leachate from the As-Built cells. This is consistent with the fact that chromium is more mobile and soluble in its oxidized state (i.e., Cr^{6+}) as compared to its reduced trivalent oxidation state (i.e., Cr^{3+}). This difference could also be the consequence of higher concentrations of dissolved organic carbon (which is captured in the TOC measurements), which has been shown to increase metal mobility through the formation of DOC-metal complexes.

Total iron concentrations in leachate as a function of time in the Control, Retrofit, and As-Built cells are presented in Figures 6-27 through 6-29, respectively. Iron concentrations showed a decreasing trend with concentrations gradually decreasing from about 15 mg/L to 5 mg/L and from about 30 mg/L to 5 mg/L in the Control and As-Built cells, respectively. In the Retrofit cells, iron concentrations showed an increasing trend in Retrofit cell A and no significant trend in Retrofit cell B and ranged from approximately 10 to 20 mg/L. Iron concentrations were higher in the Retrofit cells as compared to the Control and As-Built units. This is consistent with more reducing conditions in the Retrofit cells compared to the Control and As-Built cells. This is also consistent with the interpretation of arsenic concentrations above. Injection of air into As-Built cells appears to have had a fairly long-lasting effect as iron concentrations are low. The iron levels are likely to rebound as the waste matures and the potential effect of the aeration dissipates. However, a longer monitoring period is required to support more conclusive interpretations with respect to iron concentrations.

6.8 *Volatile and Semi-Volatile Organic Compounds*

The occurrence of VOCs and SVOCs in leachate may be of use in evaluating the landfill bioreactor's capacity for microbial assimilation and transformation of organic and potentially toxic compounds. A list of VOCs and SVOCs that were measured in the leachate of the different landfill units is presented in Chapter 3. A statistical summary of the VOCs and SVOCs detected at greater than 50 percent frequency in the different landfill units is presented in Appendix F. Similar to the discussion regarding trace metals, VOCs and SVOCs were generally only detected at fairly low concentrations in leachate from MSW landfills and meaningful trends are generally hard to discern. Overall, the concentrations of VOCs detected in leachate of the different treatment units were consistent with similar landfill settings. Acetone, MEK, and toluene were detected at a greater frequency and concentrations in the As-Built cells compared to other units. However, these compounds are generally quickly degraded under aerobic conditions and do not pose challenges for leachate management.

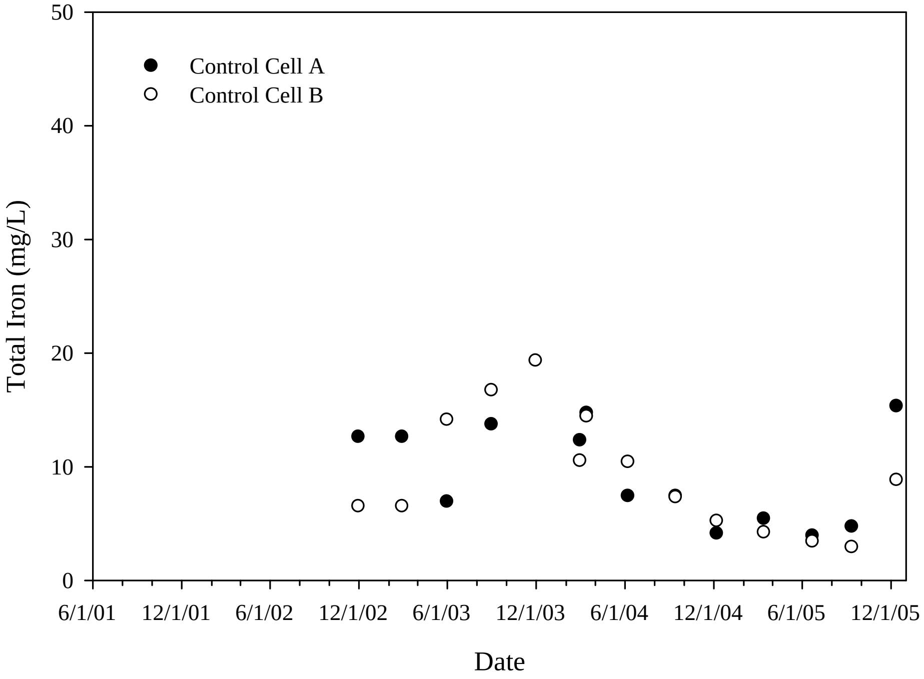

Figure 6-27 Total Iron as a Function of Time in the Control Cells

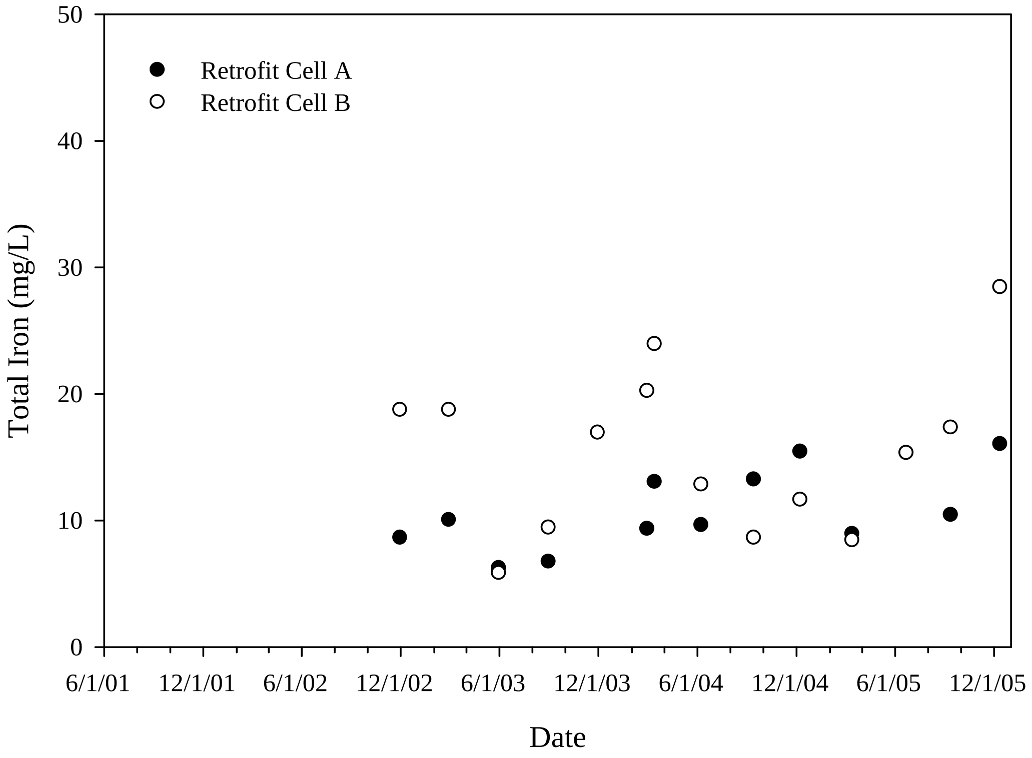

Figure 6-28 Total Iron as a Function of Time in the Retrofit Cells

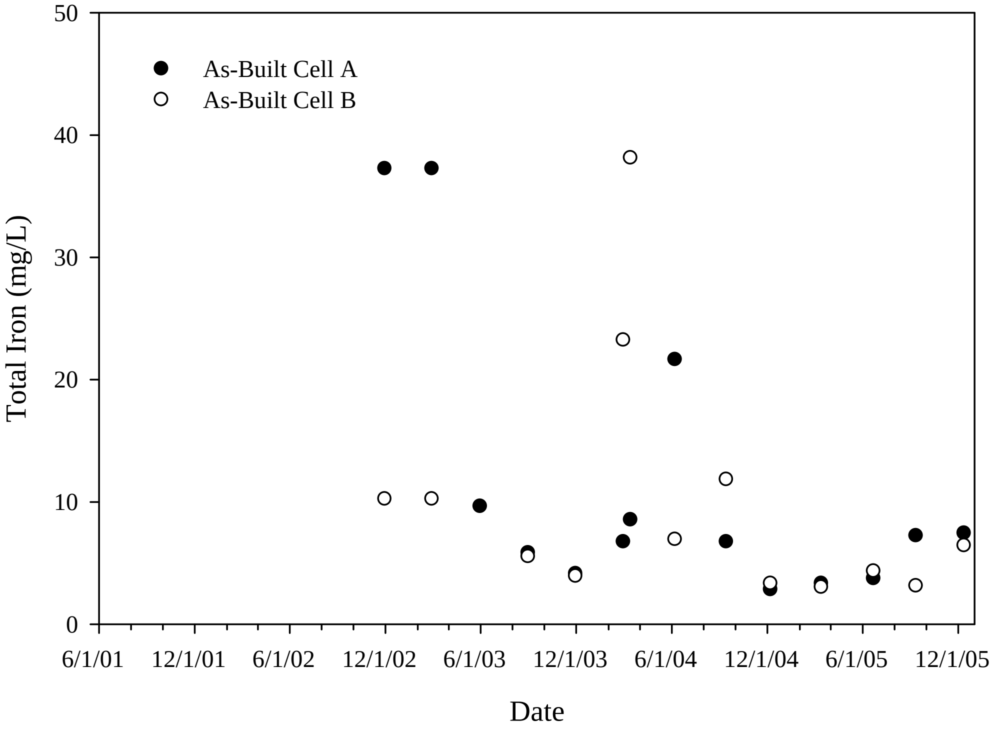

Figure 6-29 Total Iron as a Function of Time in the As-Built Cells

Similarly, leachate from MSW landfills may contain some SVOCs including phenolic compounds such as phenols and cresols. Low concentrations of cresols were detected in the As-Built cells at higher frequencies and concentrations compared to the other cells. This may be a consequence of the addition of paint waste. SVOCs and VOCs may have a small effect on COD measurements. In general, the VOC and SVOC concentrations were relatively low and there were no observed trends of VOC and SVOC concentrations in the leachate samples.

6.9 Phosphorous Content

Phosphorous may be one of the rate-controlling macro nutrients in landfills. Since leachate samples were not filtered prior to analysis, a high phosphorous concentration may be an indicator of microbial growth as it was incorporated into the microbial cell mass, which was analyzed as total phosphorous. Mineralization of organic phosphorous in the waste generates inorganic phosphorous. In its inorganic form, phosphorous is typically measured as ortho-phosphate. Leachate ortho-phosphate and phosphorous concentrations as a function of time in the Control, Retrofit, and As-Built cells, are presented in Figures 6-30 through Figure 6-35.

Phosphate concentration trends in the As-Built cells and Control cell B are similar; both show an increase over time with concentrations in the As-Built cells being slightly higher. The Retrofit cells exhibited a slightly increasing trend with lower concentrations when compared to the As-Built and Control cells. Phosphate concentrations were below 3 mg/L before they gradually increased up to 15 mg/L after the end of 2003 in the Control cells. The increase in phosphate may be an indicator of increased decomposition following the end of 2003 as organic phosphorous in waste became mineralized. On the other hand, microbial growth may account for an increase in total phosphorous concentrations, which would also be an indirect measurement of increased decomposition as an increase in microbial cell mass, suggesting an increase in waste decomposition.

Total phosphorous concentration trends are generally a reflection of phosphate concentrations. Similar to phosphate, phosphorous concentrations in the Control cells increased from below 5 mg/L to about 15 mg/L following the end of 2003. Similar to other parameters discussed above, a decrease in phosphate and phosphorous concentrations of about 5 mg/L was observed in Control cell A following the end of 2004.

The Retrofit cells displayed a slightly increasing trend with lower concentrations of phosphate and phosphorous compared to Control cell B and the As-Built cells. Phosphate and phosphorous concentrations were at or slightly below 5 mg/L in the Retrofit cells.

The As-Built cells displayed an increasing trend of phosphate and phosphorous concentrations, similar to that in the Control cells. Phosphate concentrations were mostly below 5 mg/L before they increased up to 18 mg/L following mid 2004. Similarly, total phosphorous concentrations were below 10 mg/L before increasing up to 25 mg/L following mid 2004. The increase in phosphate and phosphorous may be an indicator of increased waste decomposition and microbial growth following mid 2004. However, it cannot be excluded that the addition of the beverage waste to the As-Built cells increased the phosphorous concentrations in these cells, since many beverages contain phosphoric acid; however, this cannot be verified with the available analytical data for the beverage waste

Leachate carbon to phosphate ratio (C: P) was determined for the different treatment units. For the Control cells, the C:P ratio mean and standard deviation were 124.1 ± 69.5 (Control cell A) and 124.2 ± 53.3 (Control cell B). For the Retrofit cells, the C:P ratio mean and standard deviation were 105.3 ± 40.4 (Retrofit cell A) and 121.2 ± 53.4 (Retrofit cell B). For the As-built cells, the C:P ratio mean and standard deviation were 160.1 ± 77.7 (As-Built cell A) and 181.0 ± 58.5 (As-Built cell B). A C: P ratio of 60:1 is deemed optimal for microorganisms to actively assimilate substrate carbon.

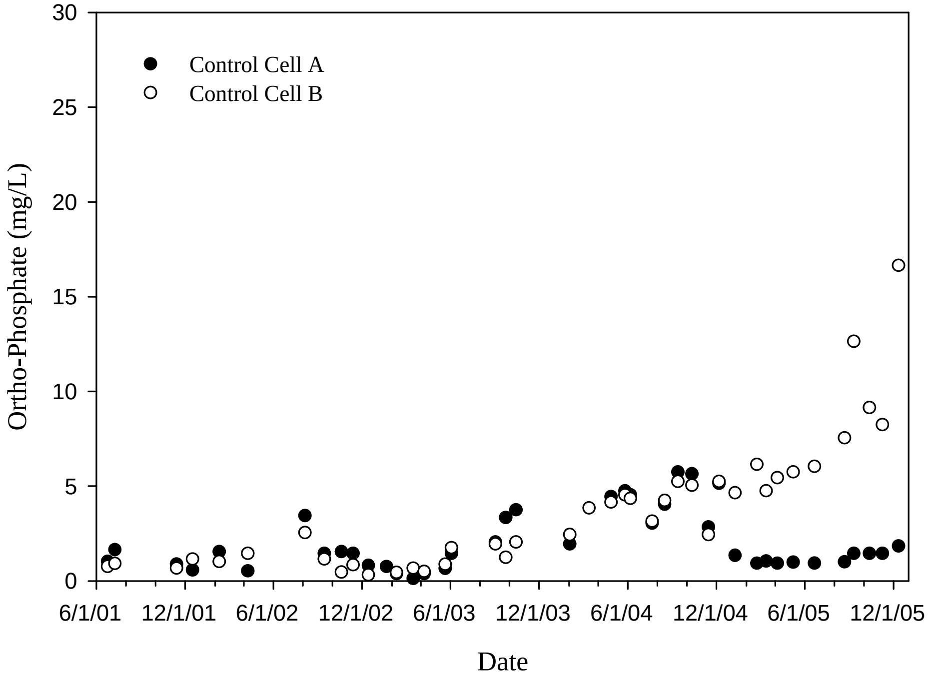

Figure 6-30 Ortho-Phosphate as a Function of Time in the Control Cells

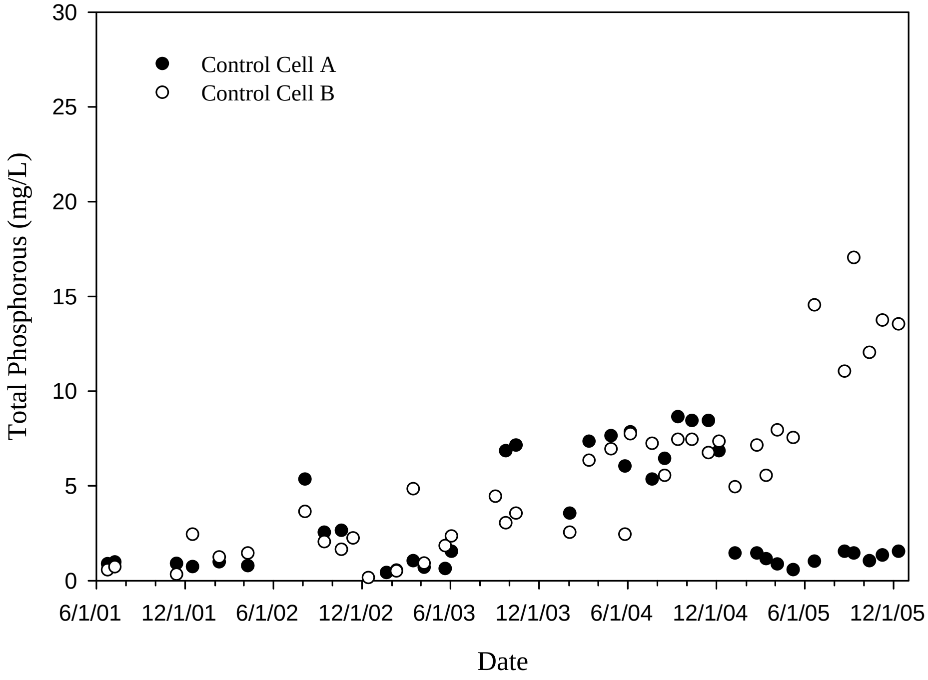

Figure 6-31 Total Phosphorous as a Function of Time in the Control Cells

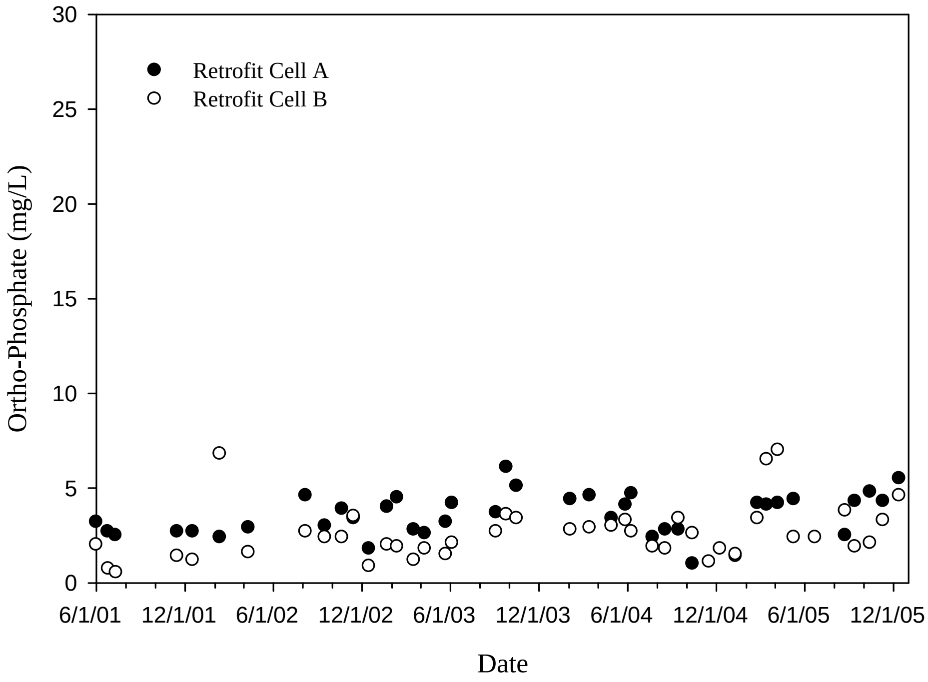

Figure 6-32 Ortho-Phosphate as a Function of Time in the Retrofit Cells

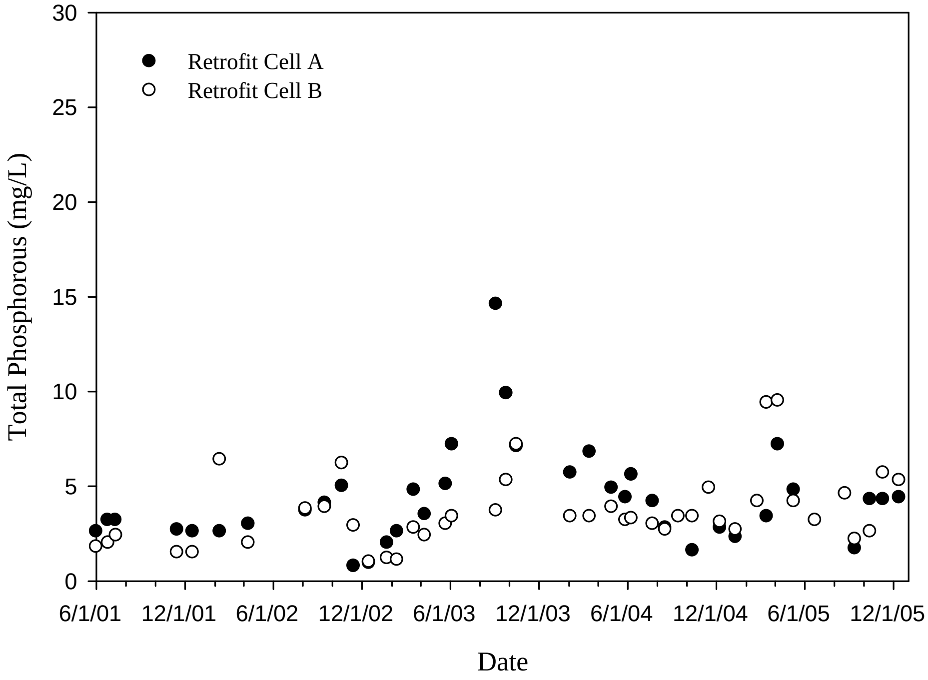

Figure 6-33 Total Phosphorous as a Function of Time in the Retrofit Cells

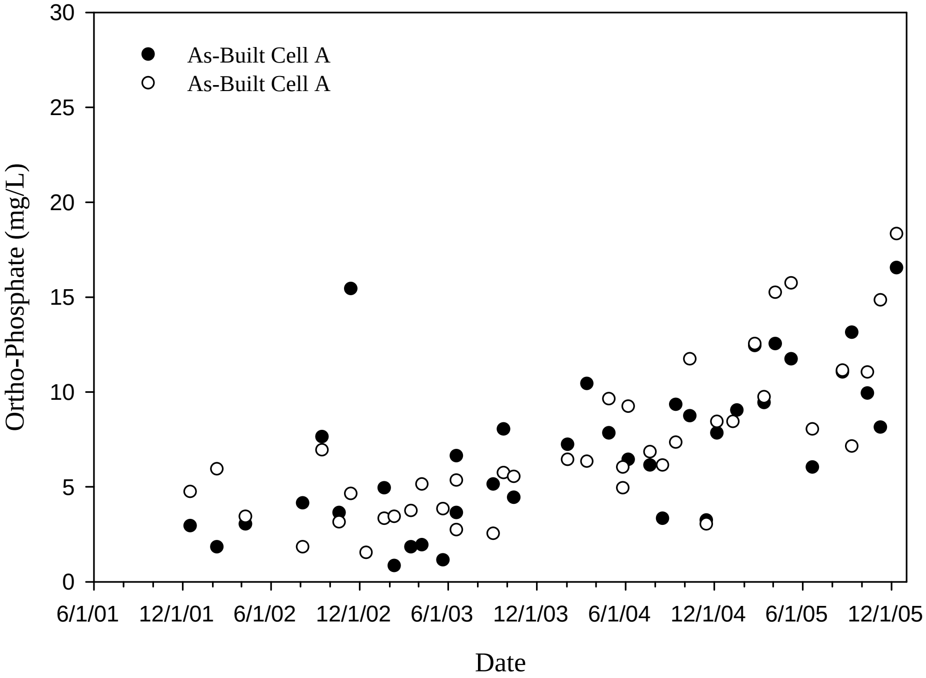

Figure 6-34 Ortho-Phosphate as a Function of Time in the As-Built Cells

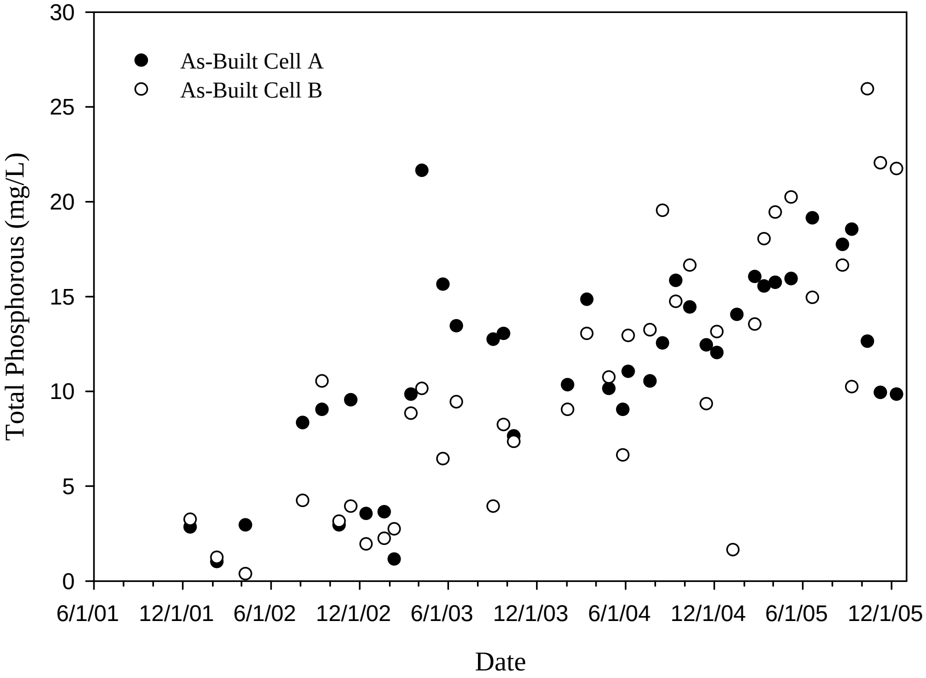

Figure 6-35 Total Phosphorous as a Function of Time in the As-Built Cells

6.10 Chloride

Chloride is a useful leachate parameter since it is present at substantial concentrations in MSW landfill leachate behaves like a conservative tracer (i.e., it does not get attenuated). Chloride concentrations are expected to show a peak due to an initial period of leaching and mobilization and remain relatively constant thereafter. Thus, chloride concentrations are generally considered to be fairly stable over time (except if the nature of the landfilled waste changes). Furthermore, chloride is not redox sensitive and should not change much as a result of the different treatment approaches.

Leachate chloride concentrations as a function of time in the Control, Retrofit, and As-Built cells are presented in Figures 6-36 through Figure 6-38. Interestingly, chloride concentrations appeared to show an increasing trend over time in both the Control and the As-Built cells, although it is observed that the initial chloride concentration in the Control cells was lower than the other cells. Changes in chloride concentrations are generally more a reflection of dilution rather than a result of waste decomposition. Chloride concentrations in the Control cells were below 1,000 mg/L prior to mid 2003 and increased to a peak at about 5,000 mg/L before decreasing again at the end of 2004. Consistent with most parameters presented in this section, chloride concentrations in Control cell A decreased compared to Control cell B following mid 2004. In the Retrofit cells, chloride concentrations showed no trend and ranged between 1,000 mg/L to 2,000 mg/L. Chloride concentrations in the As-Built cells showed an increasing trend with concentrations increasing from about 1,000 mg/L to 3,000 mg/L. The increase in chloride concentrations in the Control and As-Built cells may have been caused by the ongoing waste placement in those cells until 2004 and 2005, respectively. It is expected that these concentrations will stabilize over time.

6.11 Leachate Quality Summary

In summary, all parameters measured provide a consistent geochemical picture for each cell with respect to each cell's waste age and waste decomposition phase. The As-Built cells, which received air and liquids injection, have the youngest waste age and appear to display the most active phase of decomposition. Trends are generally not much different in the bioreactor landfill cells compared to the Control cells, even though concentrations of some parameters appear to be higher. The substantial difference in temperature, however, may indicate more active decomposition in As-Built cells, possibly reflective of the exothermic nature of aerobic MSW decomposition. Although the overall waste age in the As-Built cells is less than that of the Control cells, the geochemical analysis of the leachate indicates that the cells are approximately at the same stage of waste decomposition. Judging from the reviewed data, it can be hypothesized that the combined treatment of air and liquids appears to have accelerated waste decomposition in this investigation. The Retrofit cells, which received nitrified leachate, did not show any significant signs of accelerated waste decomposition based on the leachate chemistry. This is likely the result of waste age (as much as six years old when treatment began), which is significantly older than both the Control and As-Built units. The waste in the Retrofit cell may have already reached a more mature stage prior to the addition of supplemental liquids, which is reflected in stable and lower concentrations of many leachate parameters reviewed. From a geochemical perspective, it appears the waste may have already gone through most of its decomposition; thus, the injection of liquids did not increase waste decomposition in the Retrofit cells. The addition of nitrified leachate to the Retrofit cells resulted in a significant decrease of ammonia concentrations in the leachate of the Retrofit cells.

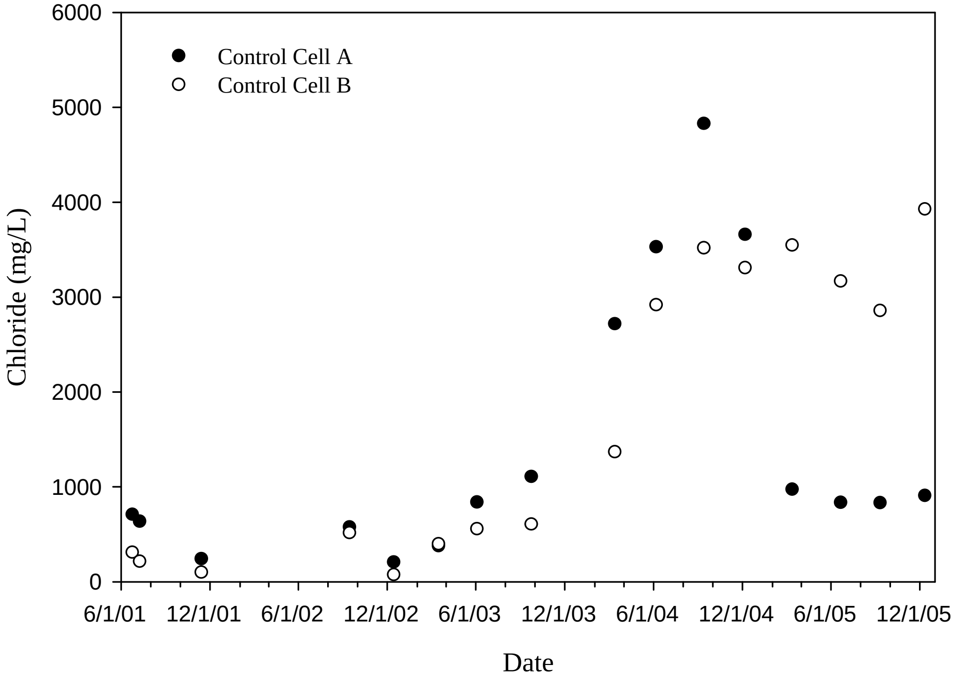

Figure 6-36 Chloride Concentrations as a Function of Time in the Control Cells

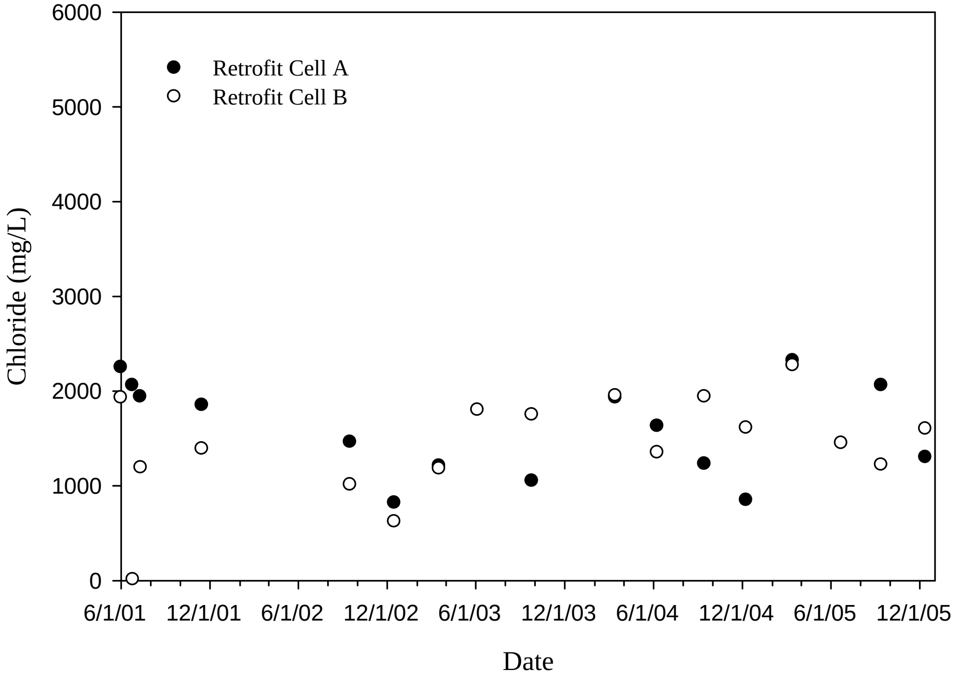

Figure 6-37 Chloride Concentrations as a Function of Time in the Retrofit Cells

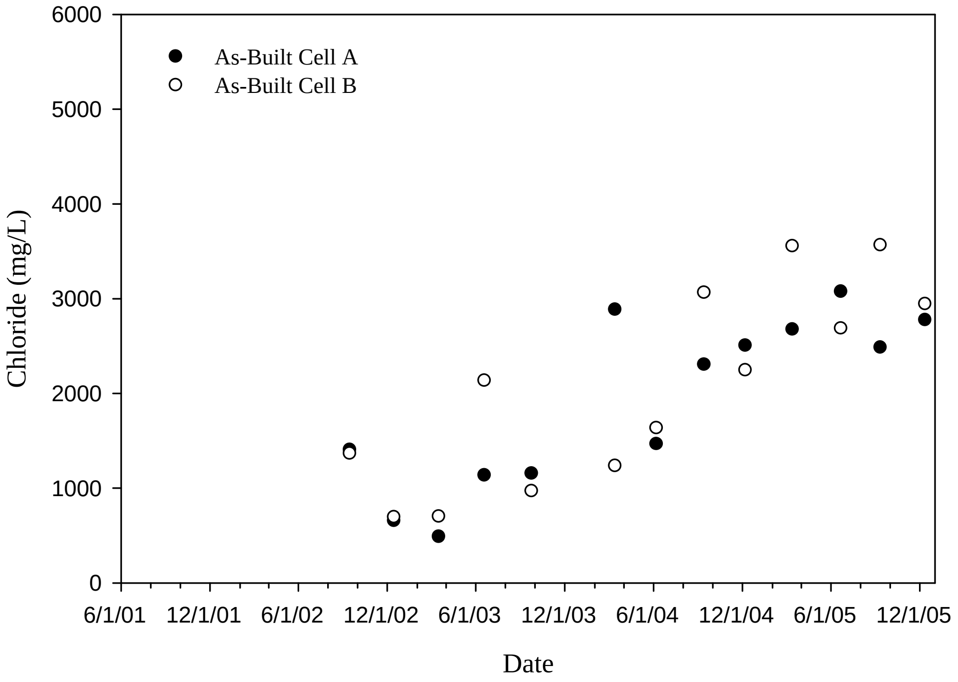

Figure 6-38 Chloride Concentrations as a Function of Time in the As-Built Cells

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Chapter 7. Landfill Bioreactor Performance Analysis

As described in Chapter 1 of this report, one of the primary objectives of the OLLB study was to evaluate whether the benefits of landfill bioreactors as reported in laboratory- and pilot-scale projects could be realized at a full-scale and operating MSW landfill. The previous chapters of this interim report focused on describing the tests that were performed to evaluate the performance of the OLLB and presenting an interpretation of the test results. This chapter provides a general discussion of the overall performance of the OLLB with respect to certain permitting issues that are relevant to landfill bioreactors. The issues addressed in this chapter are slope stability, liner and cover integrity, liquids addition system performance, LCS performance, and LFG production and emissions. Relevant sections of the "*Solid Waste Disposal Facility Criteria Technical Manual*" (U.S. EPA, 1993) are referenced, where appropriate.

7.1 Slope Stability

MSW Landfills must be designed and operated in a manner that maintains the stability of natural and waste slopes. Based on evaluations of past failures of both natural slopes and waste slopes, it is widely known that excessive amounts of liquids within soils or waste can contribute to failure and/or movement of slopes. The failure to control liquids within a slope or a landfill could result in problems related to slope stability. Because bioreactor landfill operations involve adding liquid to the wastes, it is appropriate to pay particularly close attention to the potential destabilizing effects of liquids at such facilities. Excess liquids can result in saturation and a decrease in the effective stress within the waste, with a corresponding decrease in effective shear strength. Control of excess liquid (i.e., "pore") pressures in a bioreactor landfill is provided by minimizing the potential for large portions of the landfilled waste to become saturated. This can be provided by: (i) controlling liquid application rates; (ii) maintaining the LCS operation and preventing the LCS from being overloaded; and (iii) controlling exit gradients (i.e., seeps), usually achieved by providing a minimum of 15 – 30 m (50 to 100 ft) between landfill slopes and the end of an injection pipe and/or trench.

As described in Section 4.2 (i.e., Moisture Addition) of this report, the data from the OLLB collected under the CRADA to date show that: (i) liquid application rates resulted in increased moisture content but not saturation of the waste as some of the solid waste samples examined had low moisture content; (ii) the LCS remained functional and showed no signs of excessive head buildup; and (iii) there was no evidence of excessive seeps occurring. Based on these findings, it is concluded that operation of the OLLB has not caused conditions that would decrease the stability of natural or waste slopes resulting from the development of excess pore pressures. Note that adding liquid increases the weight of the waste and, therefore, could reduce the overall stability of the waste. Although evaluation of this aspect of slope stability is beyond the scope of this report, it is likely that the increased weight resulting from moisture content increases (which are reported in Section 4.2 to be about, on average, six to seven percent in the As-Built cells and one percent in the Retrofit cells) would not have a significant adverse effect on stability if the slopes were originally designed having a factor of safety meeting the recommendations provided in U.S. EPA (1993).

7.2 Liner and Final Cover Integrity

The integrity of the base liner is of particular concern for bioreactor landfills because of the need to contain the additional amount of liquid that is collected and removed from atop the liner of a bioreactor landfill. In addition, the integrity of the final cover is of concern for a bioreactor landfill because it may be exposed to more seeps and differential settlement than a non-bioreactor landfill. The study reported in this document was not designed to evaluate liner and final cover integrity, and so this study does not directly provide information for evaluating effects of bioreactor operations on liner or cover integrity. However, it is important to note that a recent U.S. EPA study on the performance of Subtitle D landfill liner systems of landfills that are younger than 15 years old (U.S. EPA 2002) confirmed that the integrity of well-constructed liner systems that are properly monitored during construction is not jeopardized over the operating life of the facility. Leakage in the base liner is usually associated with poor construction, inadequate construction quality assurance (CQA) monitoring, and construction of features near the liner. The best assurance that the liner system will perform well for operating landfill bioreactors is to provide a high-quality construction and CQA monitoring (paying particular attention to sealing around all penetrations) and installing liquid application features in a manner that does not damage the liner (e.g.,not installing liquid application wells to a depth near the liner). Based on a review of the installation of the liquid application features for the OLLB project, there is no indication that the base liner system at the OLLB was compromised while installing liquid application features or while applying liquid through those features at this point of the project.

The integrity of the final cover could be compromised if excessive differential settlement occurs or if slope instability occurs. These problems could be worsened if landfill bioreactor operations increase the amount of differential settlement or increase the pressure on the bottom of the cover system (e.g., liquid pressure or gas pressure acting on the bottom of the geomembrane or clay barrier layer), which could lead to instability. Because final cover has not yet been installed over the cells that were part of the OLLB study, an evaluation of these potential effects. However, the lack of leachate breakout problems and the lack of landfill gas emission problems suggest that the OLLB has been operated in a manner that will minimize problems related to excessive pressures under the liner. Although no similar information is available to evaluate the potential for significant differential settlements, such settlements (if they were to occur) could be easily repaired. Based on these considerations, impacts on the integrity of the OLLB final cover are not expected to be a problem.

7.3 Liquids Addition System Performance

The performance of the liquid addition system can have a significant effect on other systems present at a landfill. Systems that could be affected include the surface-water management system (which could be affected if seeps from the landfill impinge on drainage features), LFG management system (which could be affected if gas extraction wells become filled with liquid), or the LCS (which is discussed separately in Section 7.4). Based on observations at the site, no significant leachate breakout problems were reported that would have resulted in surface-water quality effects. Therefore, the operational practices used at the OLLB appear to have been successful in preventing surface-water quality problems. Also, although there were indications of “watering-out” of gas collection wells and trenches during some periods of the study, there was also an increase in landfill gas collected from the bioreactor areas and so it is not possible to conclude whether the watering-out of the collection features would be expected to have an impact on future stability of the landfill cover system; see Section 8 for recommendations on future monitoring and performance evaluation of the LFG management system. Finally, as discussed in the body of the report, wastes having a low pH and/or high sugar levels are expected to have an adverse effect on waste degradation and should be avoided unless lab- or bench-scale testing is performed to assess the potential effects of the candidate liquid waste stream on the microbial populations and resulting performance of the landfill environmental protection systems.

7.4 Leachate Collection System Performance

If liquid application activities promote microbial activity within LCS features, then it is conceivable that those features could become clogged. In that case, the LCS features might not function as originally intended and cease to transmit leachate from the landfill as designed. Upon achieving field capacity or if preferential flow paths develop in the solid waste, there is a concern that the amount of liquids that pass into and through the LCS will increase, thus raising the concern regarding the integrity of the LCS. This concern could extend from an increase in flow volume or flow rate in the drainage materials or the premature “fouling” of the pores in either the protective geotextile or the hydraulically transmissive granular drainage component of the LCS. Although it is certainly recognized that this can be a potential problem, the authors are not aware of any case where the concern has been suspected, studied, and confirmed. It is encouraging to note that the effect of the landfill bioreactor performance is to merely accelerate the waste degradation processes, not introduce new mechanisms or processes. Therefore, components or construction techniques that are effective for the LCS systems for conventional landfills are anticipated to be effective for landfill bioreactor landfills. Because of the likelihood for additional microbial activity and higher flows rates in landfill bioreactors compared to conventional landfills, it may be advisable to consider increasing LCS hydraulic conductivity and transmissivity for landfills bioreactor projects. In addition to the construction and materials selection controls, it is recommended that operating practices that result in the potential for clogging or blinding of the LCS components be avoided. For example, if waste streams are identified that may react and introduce precipitates (e.g., aluminum dross), these waste streams should be avoided. Similarly, the use of fine-grained soils near the bottom of the waste mass should not be used, as they have the potential for migration into the LCS.

Signs of clogging of the LCS can include reduced leachate collection rates, watered-out landfill gas collection wells, or breakouts at the sides of the landfill. At the OLLB, none of these conditions was observed to the degree that would imply clogging of the LCS features. However, this finding should be confirmed again in future studies.

7.5 Landfill Gas Production and Emission

A final concern regarding landfill bioreactors is the emissions from the facility that result from enhanced LFG generation. If LFG emissions at a bioreactor landfill are greater before capping than for a non-bioreactor landfill, then it could be expected that a greater quantity of landfill gases would be emitted to the atmosphere from the bioreactor landfill. Chapter 5 indicates that, at the OLLB, LFG production in the As-Built cells was significantly higher than would be expected for a conventional dry tomb landfill and slightly higher in the Retrofit cell. However, despite the higher gas production rates during bioreactor operations, there does not appear to have been excessive surface (surface scans with greater than 500 ppm CH_4) emissions from the facility.

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Chapter 8. Conclusions and Recommendations

8.1 Conclusions

The data set from the five-year study at the OLLB represents one of the most comprehensive compilations of information regarding the performance of landfill bioreactors. The study was conducted at a full-scale operating MSW landfill and, as such, was faced with the challenges of performing leading-edge research at an operating landfill site. The objectives of the OLLB study were presented in Chapter 1; a summary of these objectives and their status (i.e., "met", "not met", or "on-going") as of the date of this Second Interim Report is presented in Table 8-1.

Table 8-1 OLLB Objectives Assessment

Objective	**Met / Not Met / On-going**	**Comment**
Design and implement two alternative large-scale bioreactor operations.	Met	The Retrofit and As-Built cells represent the two alternative bioreactor operations.
Monitor sufficient parameters to understand the physical, chemical, and biological activities within the landfill bioreactors.	On-going	Several conclusions are presented in this report; however, research and performance monitoring continues at the site.
Compare and contrast monitoring results with the requirements for a Subtitle D Landfill.	On-going	Many comparisons between the bioreactor and Control cells are provided in this report; however, research at the site is on-going.
Incorporate statistical techniques to assess effectiveness of the landfill bioreactor operation.	On-going	Statistics were utilized to evaluate data for all three media (solid, liquid, and gas). More data are being collected at the site for future statistical assessment.
Establish best practices and procedures required to operate landfill bioreactors.	On-going	Additional data collection and analysis will further refine conclusions reached in this report, leading to a complete evaluation of the operational techniques used.
Establish important and indicative parameters that should be monitored with respect to landfill bioreactor operations.	On-going	Monitoring parameter recommendations for bioreactor landfills in general are provided below in Section 8.2. Ongoing work at the site will expand on these recommendations.
Obtain sufficient data to enable improvements that may be applied to future bioreactor landfills, in both an experimental and practical capacity.	On-going	Recommendations for additional data collection parameters are provided in Section 8.3.

8.1.1 Solids Analysis

The intent of the solids decomposition analysis was to assess the reproducibility of the data between the cells and their replicates (i.e., Control cells A and B, Retrofit cells A and B, and As-Built cells A and B) and to evaluate whether the solids decomposition data support the concept that operation as a bioreactor landfill accelerates waste decomposition relative to operation as a conventional landfill. The assessment of cell replicates indicated that the waste in the Retrofit and Control cell replicates were similar, but As-Built cells A and B were found to be significantly different. The differences between As-Built cell A and As-Built cell B were attributed to the fact that the waste in the two cells was relatively young.

The three primary parameters used to assess the extent of decomposition were BMP, CH:L, and organic solids content. Generally, a decrease in these parameters indicates an increase in the degree of waste decomposition. CH:L and organic solids content were found to be significantly different in the Retrofit cells compared to the Control cells; however, linear regressions of the data indicated that BMP was similar in the Retrofit and Control cells. All three decomposition parameters were less in As-Built cell A relative to both the Control cells and As-Built cell B, indicating more rapid waste decomposition. The accelerated waste decomposition in As-Built cell A relative to As-Built cell B was attributed to the much larger volume of air injected into As-Built cell A (approximately five times greater on a mass basis). However, regressions of solids data for As-Built cell B did not indicate a difference when compared to the Control cells. One limitation of the analysis of the As-Built cells was the young age of the waste, which precluded significant trends in waste decomposition to develop. An additional limitation in developing strong trends in decomposition was the inherent heterogeneity of the MSW. Despite nearly five years of operation, the solids analysis results still indicate that, although there are statistical differences in waste decomposition between the three distinct cells, the waste has not undergone significant solids decomposition. It is expected that data from sampling and testing of solid waste from these cells in subsequent years will show more consistent solids decomposition trends.

8.1.2 Liquids Analysis

The liquids analysis involved assessing the moisture balance of the different landfill cells, evaluating leachate head on the liner, and evaluating leachate quality data. Data showed an inconsistent trend in moisture content with respect to waste age and the type of landfill cell. For instance, the mean measured moisture content for the Control cells showed an overall increase of approximately six percent between 2002 and 2005, which is a large increase considering that no moisture was added to the Control cells during the study period. Overall, measured waste moisture content data as obtained from moisture content measurements on discrete waste samples should be interpreted with caution; variability in waste composition, hydraulic properties, compaction rates, and other factors likely contributed to the inconsistent behavior of the measured moisture content data.

A moisture balance was conducted using a combination of information related to rainfall, liquids addition, and leachate generation quantities. The initial moisture content percentage used in the calculation was based on the measured moisture content of samples collected in 2002, prior to initiation of liquids addition in the bioreactor landfills cells. This assumption has obvious limitations in that it represents data based on discrete samples from a single sampling event. As described earlier, the measured moisture content data showed inconsistent trends in all cells during the study period; however, this was assumed to be a more appropriate starting point compared to literature-reported moisture content values. Liquid addition rates of 5.3, 65.3, and 43.4 gallons/ton in the Retrofit cells, As-Built cell A, and As-Built cell B resulted in a calculated moisture content increase (on a wet weight basis) of approximately one, six, and seven percent, respectively. The slight increase observed in the Retrofit cells is attributed to a low liquid injection volume at those cells relative to the overall mass of the cells, as well as the cover system that minimized infiltration of rainfall. The six and seven percent moisture content increase in As-Built cell A and As-Built cell B is believed to be conservative relative to the “Liquid In” volumes that likely infiltrated the waste mass in these cells. Prior to the first quarter of 2004, a 0.3m (1 ft) thick layer of tire chips was installed between the As-Built cells, resulting in short-circuiting of injected liquids to the LCS. This led to an overall increase in the “Liquid Out” value used in the moisture balance calculation prior to the first quarter of 2004. When the practice of installing the tire chip layer between the As-Built cells ceased following the first quarter of 2004, the rate of leachate generation slowed significantly, indicating that a greater increase in moisture content may have occurred in the As-Built cells (based on the Liquid In volumes) if the tire chip layer had not been installed prior to 2004. Data following the first quarter of 2004 indicated a significantly lower leachate generation rate in the As-Built cells. Nevertheless, the moisture balance calculation results for the bioreactor landfill cells underscore the fact that very large volumes of liquid are required to significantly increase the moisture content of a landfill. Despite efforts to significantly increase the moisture content, it appears that additional liquids could have been assimilated by the waste if the operation procedures had been different.

Leachate head in the sump for each cell was measured to provide an indication of the leachate head on the liner. The mean leachate head in the sump for each cell was below the regulatory threshold of 0.3 m (1 ft). However, exceedances of head on the liner did occur occasionally in all cells; the exceedances generally corresponded with the active filling phase of a particular landfill cell, and the frequency of exceedances decreased after the final lift of waste had been placed. The exceedances during waste filling were primarily attributed to inadvertent routing of runoff from the cell to the sump.

The leachate quality analysis results were generally consistent with the corresponding calculated age of the waste for each cell throughout the study period. However, the results of the leachate quality analysis for the majority of the parameters did not reveal a strong trend that would indicate significantly accelerated waste decomposition in the bioreactor landfill cells. Still, the results of some of the parameters were encouraging. For example, the BOD/COD ratio in the As-Built cells decreased to below 0.5 within two years of initial waste placement, which is indicative of waste decomposition. In comparison, the BOD/COD ratio for the Control cells did not decrease to below 0.5 until approximately four years after initial waste placement, supporting the premise of accelerated waste decomposition in the As-Built cells. Additionally, Chapter 2 described the ex-situ nitrification process that was used to treat the leachate prior to injection into the Retrofit cells; this process, implemented with the intent of decreasing the ammonia concentration, was expected to have an increasing benefit over time as a result of increased waste decomposition. The mean ammonia concentration in the Retrofit cells showed a strongly decreasing trend during the study period, which indicates that treating the leachate ex-situ was effective at decreasing the ammonia concentration in the leachate.

8.1.3 LFG Analysis

The goals of the LFG analysis were to evaluate the LFG kinetics in each cell, draw comparisons between the cells, and assess the NMOC concentration data for each cell. Using the field-collected LFG data and in-place waste mass as inputs, the U.S. EPA model LandGEM was used to estimate waste decay rates for each cell. Assuming a 75 percent LFG collection system efficiency, waste decay rates of approximately 0.16, 0.061, and 0.06 yr^{-1} were estimated for As-Built cells, the Retrofit cells, and the Control cells, respectively. It is noted that there are some limitations to the estimation of these decay rates. First, the LFG collection efficiency was assumed based on the AP-42 recommended value of 75 percent. Second, the estimation of the decay rates was based on only three years (As-Built cells) or four and a half years (Retrofit cells) of field-collected data. Third, the CH_4 generation potential, L_o, used in LandGEM was assumed to be constant and was selected based on the analysis of fresh waste, although this value likely does not remain constant over time as waste degrades. Despite these limitations, the results strongly indicate that the LFG generation rate was accelerated in the As-Built cells relative to the Control cells. The results also indicate that the LFG generation rate in the Retrofit cells appeared to be somewhat greater than in the Control cells; however, the LFG flow and composition data from the Retrofit cells indicated a degree of variability that was attributed to the watering out of LFG collection wells. As a result, the LFG collection efficiency in the Retrofit cells may be less than the assumed 75 percent, which would indicate that the waste decay rate in the Retrofit cells may be greater than 0.061 yr^{-1}.

The NMOC concentration data were evaluated in two ways: (i) NMOC production based on the measured NMOC concentration and LFG flow data from each cell; and (ii) NMOC production based on the NMOC concentration data and mass of in-place waste for each cell. The first method was developed to tie in the years of field gas data to the NMOC concentration and to investigate any trends. The second method was similar to the method prescribed in a typical Tier 2 NSPS analysis, in which a site-specific NMOC concentration is used in LandGEM to predict NMOC production based on waste placement data. Analysis of NMOC production using the first method indicated little difference between the cells, resulting in a mean NMOC production rate of 0.012, 0.012, 0.010, and 0.008 kg/min for the Control cells, Retrofit cells, As-Built cell A, and As-Built cell B, respectively. Analysis of NMOC production using waste placement data and the mean NMOC concentration for each cell indicated NMOC production rates of less than 50 Mg/yr for each cell; it is noted that the predicted NMOC production using LandGEM was performed primarily to observe whether each cell exceeded the regulatory threshold of 50 Mg/yr of NMOCs.

8.1.4 Summary

Overall, the performance monitoring results are very encouraging. The most significant conclusion is that, despite the five-year duration of the study, two of the three media analyzed (i.e., solids and LFG) indicated that waste decomposition was accelerated in the As-Built and Retrofit cells relative to the Control cell. Table 8-2 summarizes a comparison of the different waste decomposition indicators for each media (solid, liquid, or gas) between the Control cells and the bioreactor landfill cells.

For the Retrofit cells, two of the three solids monitoring parameters indicated accelerated decomposition relative to the Control cells; therefore the results were believed to be inconclusive. Furthermore, for the Retrofit cells, the generally stable leachate data did not indicate that waste decomposition was accelerated as a result of liquids addition. The LFG results indicated a waste decay rate that was similar to that of the Control cells; the authors believe that if the actual LFG collection efficiency in the Retrofit cells could be established, it would likely reveal an efficiency of less than 75 percent, thereby resulting in a greater estimated waste decay rate.

For As-Built cell A, all three solids monitoring parameters indicated a trend of accelerated waste decomposition relative to the Control cells. The BOD/COD ratio of the leachate indicated that perhaps waste decomposition was accelerated, but that ratio alone is not enough to conclude that the leachate indicated accelerated waste decomposition. At the other extreme, the waste decay rate as estimated by using the LFG collection data in the As-Built cells was several times greater than the Control cells.

Not all of the solids monitoring parameters indicated accelerated waste decomposition in As-Built cell B relative to the Control cells. The authors believe that future solid waste sampling will likely indicate accelerated decomposition of waste in this cell. Similar to As-Built cell A, As-Built cell B exhibited a decrease in BOD/COD ratio, indicating that waste decomposition was accelerated relative to the Control cells, but as stated above this is not enough to conclude that the leachate results (by themselves) indicated accelerated waste decomposition. LFG data from As-Built cell B indicated a waste decay rate several times that of the Control cells.

Table 8-2 Evidence of Accelerated Waste Decomposition Across All Media Analyzed Between Control and Bioreactor Landfill Cells

Bioreactor Landfill Cell	Solid	Liquid	Gas
Retrofit cells	I	No	TBD
As-Built cell A	Yes	I	Yes
As-Built cell B	TBD	I	Yes

Notes:
1. TBD - To be determined; a conclusion will likely be reached after additional data is collected.
2. I - The results of the waste decomposition data were positive, but inconclusive.

8.2 Recommendations

As Table 8-2 shows, and as described in Sections 8.1.1 through 8.1.3, ongoing performance monitoring is anticipated (and is recommended) to continue at the OLLB. The parameters reported in Chapter 2 will continue to be monitored for the next several years. The authors recommend that additional analyses be considered. The results of these additional analyses could support the conclusions presented in this report. Additional recommendations are provided below:

- Collect data that can be used to estimate LFG collection efficiency for each cell. This could be accomplished by using U.S. EPA Method 2E to estimate the LFG generation rate and indirectly estimating the CE by comparing the LFG generation rate with the LFG collection rate. Alternatively, the fugitive emissions for each cell may be estimated using a technology such as open path Fourier-transform infrared spectrometry. Fugitive emissions at the OLLB were previously reported using this technique (U.S. EPA 2005), but the measurements were taken in 2002 and 2003, prior to the end of waste placement in the As-Built and Control cells.

- Continue collecting topographic survey data of the Control, Retrofit, and As-Built cells. The authors note that it may take several more years before a quantitative correlation between waste decomposition and settlement can be made for the landfill bioreactor cells.

- Provide more detailed sample identification information during the collection of solid waste samples, especially with regard to the sample proximity of a liquid addition pipe or trench. The authors believe this information may provide insight related to the variability of the measured moisture content data. For example, during solid waste sample collection, note the distance of the borehole to the nearest injection pipe/trench, and identify the volume of liquids added to the corresponding trench/pipe, if that information is available.

It may only be necessary to collect one more set of solid waste samples over the next approximately five years to analyze the various decomposition parameters. As noted in Section 4.1, a high degree of scatter seen in the data may be attributable to the relatively short time window during which the samples were collected, resulting in relatively young waste.

8.3 Landfill Bioreactor Monitoring Parameters

The OLLB will continue to monitor the parameters (presented in Chapter 2) at the same frequency for the next several years under its RD&D permit. As a result, the trends of solids decomposition, moisture balance, LFG composition and flow, and leachate quality will be further developed. It is expected that the variability seen in some trends (e.g., solids decomposition) will tend to decrease during this period, as the study cells are no longer active (i.e., the study cells no longer receive new waste). Based on the results from the first five years of monitoring at the OLLB, the following observations can be made regarding the monitoring parameters and frequency described in Chapter 2.

The mass balance and liquid addition monitoring parameters listed in Tables 2-1 and 2-2 are considered to be a fundamental part of the OLLB program and any landfill bioreactor project. The liquids added and the nature and amount of the deposited material in the landfill cell provide the basic information for conducting moisture balancing and predicting LFG generation using LandGEM. The monitoring frequency listed in Tables 2-1 and 2-2 was appropriate for the first five years of the OLLB project.

LFG monitoring of CH_4, CO_2, O_2, and balance gas once per week appeared to be an appropriate monitoring frequency for the OLLB study. Monitoring at this frequency minimized significant variability that may have occurred with less frequent monitoring; however, even with weekly sampling, there was a relatively high degree of variability in the As-Built and Retrofit bioreactor landfill cells. NMOC monitoring, however, appeared to be more frequent than needed. The comparison of NMOC production between cells did not indicate a significant difference between the bioreactor landfill cells data and the Control cell data. The authors believe an NMOC sampling frequency of once per year is adequate to further develop the trends (or lack thereof) seen in the first five years of the OLLB project. Furthermore, the authors believe that an NMOC sampling frequency of once per year at other landfill bioreactor sites may be appropriate.

Solid waste sampling and analysis parameters used for quantifying solid waste decomposition were appropriate; however, the period of the study (i.e., only five years) appears to have been too short to see significant trends, even in cells where large decomposition rates were anticipated. There was significant variability in BMP, CH:L, and organic solids between the three sampling periods; the authors believe that the scatter observed in these parameters may have been caused by the relatively short time window analyzed in this study. For bioreactor landfills in general, the authors believe that it is critical to obtain a sufficient number of solid waste samples for characterization at the outset of a bioreactor landfill project and less frequent monitoring (e.g., every five years) be conducted following the initial sampling period. Analyses on samples of solid waste are important as they provide the most direct evidence of waste decomposition. However, the solids analyses are performed on discrete samples and the inherent variability in waste composition may “mask” the indicators of decomposition during the short monitoring time period that has elapsed so far for the OLLB.

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Chapter 9. References

Aguilar, A.; Casas, C.;and J. Lema (1995). “Degradation of Volatile Fatty Acids by Differently Enriched Mehtanogenic Cultures: Kinetics and Inhibition.” Water Research 29: 505-509.

American Public Health Association (1999). Standard Methods for the Examination of Water and Wastewater, 21st Ed., 1999.

Amman, R., Ludwig W., and K-H. Schleifer. (1995). “Phylogenetic identification and in situ detection of individual microbial cells without cultivation” Microbiological Reviews, 59: 143-169.

Bachus, R., Houlihan, M., Kavazanjian, E., Isenberg, R., and J. Beech (2004). “Landfill Bioreactor Stability: Key Issues”, Municipal Solid Waste Management, Sept/Oct.

Barlaz, M., Ham, R., and D. Schafer (1989). “Mass-Balance Analysis of Anaerobically Decomposed Refuse.” Journal of Environmental Engineering, 115(6): 1088-1102.

Barlaz, M., Ham, R. and D. Schaefer, (1990). "Methane Production from Municipal Refuse: A Review of Enhancement Techniques and Microbial Dynamics.” CRC Critical Reviews in Environmental Control, 19(6): 557 - 584.

Barlaz, M., Green, R., Chanton, J., Goldsmith, C., and G. Hater (2004). “Evaluation of a Biologically Active Cover for Mitigation of Landfill Gas Emissions.” Environmental Science & Technology, 38(18): 4891 - 4899.

Barlaz, M. (2006). “Forest Products Decomposition in Municipal Solid Waste Landfills.” Waste Management, 26(4): 321 - 333.

Bookter, T., and R. Ham (1982). “Stabilization of Solid Waste in Landfills.” Journal of Environmental Engineering, ASCE, 108: 1089-1100.

Christensen, T., Kjeldsen, P., Bjerg, P., Jensen, D., Christensen, J., Baun, A., Albrechtsen, H-J., and G. Heron (2001). “Biogeochemistry of Landfill Leachate Plumes.” Applied Geochemistry, 16: 659-718.

Chu, L., Cheung, K., and M. Wong (1994). “Variations in the Chemical Properties of Landfill Leachate.” Environmental Management, 18: 105-114.

Clescerl, C., Greenberg, A., and Eaton, A. (eds.) (1999). “Standard Methods for Examination of Water and Wastewater.” American Public Health Association, 20th Edition.

Colberg, P.J. (1988). “Anaerobic Microbial Degradation of Cellulose, Lignin, Oligolignols, and Monoaromatic Lignin Derivatives.” 333-372. In A. J. B. Zehnder (ed), Biology of Anaerobic Microorganisms, Wiley-Liss, New York.

Conrad, R. (1995). “Soil Microbial Processes Involved in Production and Consumption of Trace Gases.” Advances in Microbial Ecology, 14: 207-250.

Cook, A., Rowe, R., Rittmann, B., and J. VanGulck(2001). "Biofilm Growth and Mineral Precipitation in Synthetic Leachate Columns," Journal of Geotechnical and Geoenvironmental Engineering, 10(127): 849-856.

Davis, M. (1998). “A Rapid Modified Method for Compositional Carbohydrate Analysis of Lignocellulosics by High pH Anion-Exchange Chromatography with Pulsed Amperometric Detection (HPAEC/PAD),” Journal of. Wood Chemical Technology, 18(2): 235-252.

Eklund, B., Anderson, E., Walker, B., and D. Burrows (1998). "Characterization of Landfill Gas at the Fresh Kills Municipal Solid Waste Landfill.” Environmental Science and Technology, 32: 2233-2237.

Eleazer, W., Odle, W., Wang, Y. and M. Barlaz, (1997), “Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills,” Environmental Science and Technology, 31(3): 911 - 197.

El-Fadel, M. (1998). "Leachate Recirculation Effects on Settlement and Biodegradation Rates in MSW Landfills," Environmental Technology, 20: 121-134.

Haydar, M.and M. Khire (2006). “Leachate Recirculation Using Horizontal Trenches in Bioreactor Landfills.” Journal of Geotechnical & Geoenvironmental Engineering, ASCE, 131(7): 837-847.

Haydar, M.M. and M. Khire (2006). “Leachate Recirculation Using Permeable Blankets in Engineered Landfills.” Journal of Geotechnical & Geoenvironmental Engineering, ASCE, 133(2): 166-174.

Fleming, I., Rowe, R., and D. Cullimore (1999). "Field Observations of Clogging in a Landfill Leachate Collection System," Canadian Geotechnical Journal: 36, 685-707.

Foose, G., Benson, C., and T. Edil (2002). “Analytical Equations for Predicting Concentrations and Mass Flux from Composite Liners” Geosynthetics International, 8(6): 551-575.

Gadd, G. (1992). “Metals and Microorganisms: A Problem of Definitions.” FEMS Microbiology Letters, 100: 197-203.

Gonzalez, G.; Urrutia, H.; Roeckel, M.; and E. Aspe (2005). “Protein Hydrolysis under Anaerobic, Saline Conditions in Presence of Acetic Acid.” Journal of Chemical Technology and Biotechnology, 80(2): 151-157.

Federal Register (2003). National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills; 68(11): 2227-2242.

Federal Register (2004). Research, Development, and Demonstration Permits for Municipal Solids Waste Landfills; 69(55): 13242-13256.

Halvadakis, C., Findikakis, A., Papelis, C., and J. Leckie (1988). “The Mountain View Controlled Landfill Project Field Experiment.” Waste Management and Research, 6: 103-114.

Ham, R. and T. Bookter (1982). "Decomposition of Solid Waste in Test Lysimeters," ASCE, J. of Environmental Engineering, 108(EE6): 1147 - 70.

Hansen, K., Angelidaki, I., and B. Ahring (1998). "Anaerobic Digestion of Swine Manure Inhibition by Ammonia." Water Research, 32(1): 5-12.

Hartz, K., Klink, R., and R. Ham (1982). "Temperature Effects: Methane Generation from Landfill Samples." Journal of Environmental Engineering, 108(4): 629-638.

Hashimoto, A. (1986). "Ammonia Inhibition of Methanogenesis from Cattle Wastes." Agricultural Wastes, 17: 241-261.

Hossain, M., Gabr, A., and M. Barlaz, M. (2003). “Effect of Decomposition and Stress on Creep Compression Index of Municipal Solid Waste in Landfill bioreactors.” The 12th Pan-American Conference for Soil Mechanics and Geotechnical Engineering and the 39th US Rock Mechanics Symposium, Soil and Rock America 2003, June 22-26, Cambridge, Massachusetts, USA: 1435-1440.

Hugenholtz, P.; Goebel, B.; and N. Pace. (1998). “Impact of Culture-Independent Studies on the Emerging Phylogenetic View of Bacterial Diversity.” Journal of Bacteriology, 180(18): 4765-4774.

Hughes, M., and K. Poole (1989). Metals and Micro-organisms. Chapman and Hall, New York

Ikem, A.; Osibanjo, O.; Sridhar, M.; and A. Sobande (2002). “Evaluation of Groundwater Quality Characteristics near Two Waste Sites in Ibadan and Lagos, Nigeria.” Water Air and Soil Pollution, 140 (1-4): 307-333.

Intergovernmental Panel on Climate Change (2001). Climate Change 2001: The Scientific Basis, Cambridge University Press, United Kingdom.

Jain, P., Powell, J., Townsend, T., and D. Reinhart (2005). “Air Permeability of Waste in a Municipal Solid Waste Landfill.” Journal of Environmental Engineering, ASCE, 131(11): 1565-1573.

Jain, P., Powell, J., Townsend, T., and D. Reinhart (2006). “Estimating the Hydraulic Conductivity of Landfilled Municipal Solid Waste Using the Borehole Permeameter Test.” Journal of Environmental Engineering, ASCE. 132(6):645-652.

Jones, K., Rees, J., and J. Grainger, (1983). “The Application of Enzyme Activity Measurements to a Study of Factors Affecting Protein, Starch and Cellulose Fermentation in Domestic Refuse,” Eur. J. Appl. Microbiol. Biotechnol., 18: 181-185.

Jjemba, P. (2004). Environmental Microbiology: Principles and Applications. Science Publishers: Enfield, NH.

Kim, J., and F. Pohland (2003). “Process Enhancement in Anaerobic Landfill bioreactors.” Water Science and Technology, 48(4): 29-36.

Kjeldsen, P., Barlaz, M., Rooker, A., Baun, A., Ledin, A., and T. Christensen (2002). “Present and Long-Term Composition of MSW Landfill Leachate: A Review.” Critical Reviews in Environmental Science and Technology, 32(4): 297-336.

Koerner, G., and R. Koerner (1995). “Long-Term Permeability of Granular Drainage Material.” Proceedings Seminar Publication Landfill Bioreactor Design and Operation, Wilmington, DE.

Krung, M., and R. Ham (1991). “Analysis of Long-Term Leachate Characteristics.” Sardinia International Landfill Symposium, Cagliari, Italy: 9-12.

Landva, A. and J. Clark (1990). “Geotechnics of waste fills.” ASTM STP1070 Geotechnics of Waste Fills: Theory and Practise: 86-103.

Lay, J., Li Y., and Tatsuya, N. (1998). “Mathematical Model for Methane Production from Landfill Bioreactor.” Journal of Environmental Engineering. 19: 730-736.

McCarty, P. (1964). “Anaerobic Waste Treatment Fundamentals.” Public Works, 9-12.

Mehta, R., Barlaz, M. A., Yazdani, R., Augenstein, D., Bryars, M. and L. Sinderson (2002). “Refuse Decomposition in the Presence and Absence of Leachate Recirculation.” J. Environmental Engineering, 128(3): 228-236.

Olayinka, A. (2003). “Microbial Respiration and Nitrate Production in Cowdung Amended Alfisol as Affected by Temperature and Moisture Content.” Discov. Innov., 15(1-2): 75-82.

Parkin, G., and F. Owen (1986). “Fundamentals of Anaerobic Digestion of Wastewater Sludges.” Journal of Environmental Engineering, 112(5): 867-920.

Petterson, R., and V. Schwandt (1991). “Wood Sugar Analysis by Anion Chromatography.” Journal of Wood Chemical Technology, 11: 495-501.

Pohland, F. (1975). “Sanitary Landfill Stabilization with Leachate Recycle and Residual Treatment.” EPA-600/2-75-043, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Pohland, F., and S. Harper (1987). “Retrospective Evaluation of the Effects of Selected Industrial Wastes on Municipal Solid Waste Stabilization in Simulated Landfills.” Georgia Institute of Technology, School of Civil Engineering, Atlanta, Georgia, 251 pp.

Pohland, F., Cross, W., Gloud, J., and D. Reinhart (1993). “Behavior and Assimilation of Organic and Inorganic Priority Pollutants Co-disposed with Municipal Refuse.” EPA/600/R-93/137a, Risk Reduction Engineering Laboratory Office of Research and Development, Cincinnati, Ohio.

Pohland, F., and B. Al-Yousfi (1994). “Design and Operation of Landfills for Optimum Stabilization and Biogas Production.” Water Science and Technology, 30(12): 117-124.

Powell, J., Jain, P., Kim, H., Townsend, T., and D. Reinhart (2006). “Changes in Landfill Gas Quality as a Result of Controlled Air Injection.” Environmental Science and Technology, 40: 1029-1034.

Price, G., Barlaz, M. and G. Hater, (2003), “Nitrogen Management in Bioreactor Landfills.” Waste Management, 23(7): 675 - 88.

Reinhart, D., and B. Al-Yousfi (1996). “The Impact of Leachate Recirculation on Municipal Solid Waste Landfill Operating Characteristics.” Waste Management and Research, 14: 337-346.

Reinhart, D., and T. Townsend (1998). Landfill Bioreactor Design and Operation, Lewis Publishing, New York.

Rittmann, B., Banaszak, J., Cooke, A., and R. Rowe (2003). “Biogeochemical Evaluation of Mechanisms Controlling $CaCO_{3(s)}$ Precipitation in Landfill Leachate Collection Systems.” Journal of Environmental Engineering, 129(8), 723-730.

Ress, B., Calvert, P., Pettigrew, C. and M. Barlaz (1998). “Testing Anaerobic Biodegrability of Polymers in a Laboratory-Scale Simulated Landfill,” Environmental Science & Technology, 32(6): 821 - 827.

Rhew, R. and M. Barlaz, (1995), "The Effect of Lime Stabilized Sludge as a Cover Material on Anaerobic Refuse Decomposition," Journal of Environmental Engineering, 121(7): 499 - 506.

Rowe, K., Armstrong, M., and D. Cullimore (2000). “Particle Size and Clogging of Granular Media Permeated with Leachate.” Journal of Geotechnical and Geoenvironmental Engineering, 126(9): 775-786.

Schroeder, P., Dozier, T., Zappi, P., McEnroe, B., Sjostrom, J. and L. Peton (1994). “The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3.” EPA/600/R-94/168b, US. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH.

Sheridan, S (2002). Modeling Solid Waste Settlement as a Function of Mass Loss, Master Thesis, University of Florida. Gainesville FL.

Singh, S. and B. Murphy (1990). “Evaluation of the Stability of Sanitary Landfills.” Geotechnics of Waste Landfills - Theory and Practice” Landva, A. and Knowles, G.D., Editors, ASTM Special Publication 1070, proceedings of a symposium held in Pittsburgh, Pennsylvania, USA: 240-258.

Sponza, D.; and O. Agdag (2004). “Impact of Leachate Recirculation and Recirculation Volume on Stabilization of Municipal Solid Wastes in Simulated Anaerobic Bioreactors.” Process Biochem., 39(12): 2157-2165.

Staley, B., Xu, F., Cowie, S., Barlaz., M., and Hater, G. (2006) “Release of Trace Organic Compounds During the Decomposition of Municipal Solid Waste Components”. 40:5984-5991

Tchobanoglous, G., Theisen, H., Vigil, S. (1998). Integrated Solid Waste Engineering Principles and Management Issues. New York: McGraw-Hill.

Tiquia, S. M.; Wan, J. H. C.; Tam, N. F. Y. (2002). “Dynamics of Yard Trimmings Composting as Determined by Dehydrogenase Activity, Atp Content, Arginine Ammonification, and Nitrification Potential.” Process Biochem., 37(10): 1057-1065.

Townsend, T., Miller, W., Lee, H., and J. Earle (1996). “Acceleration of Landfill Stabilization Using Leachate Recycle.” Journal of Environmental Engineering, 122(4): 263-268

Townsend, T., and L. Miller (1998). “Leachate Recycling Using Horizontal Injection.” Advances in Environmental Research. 2(2):129-138.

U.S. Department of Commerce, National Climatic Datacenter (2004). Climatology of the United States No. 20, 1971-2000, Louisville Standiford AP, KY Station.

U.S. EPA (1987). Guidance Manual for Preventing Interference at POTWs, September 1987.

U.S. EPA (1993). “Solid Waste Disposal Facility Criteria.” U.S. EPA 530/R-93/017; U.S. EPA: Cincinnati, Ohio.

U.S. EPA (1996). Test Methods for Evaluating Solid Waste: Physical/Chemical Methods, EPA Office of Solid Waste.

U.S. EPA (1998). Compilation of Air Pollutant Emission Factors, 5th Edition: EPA AP-42; U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Supplement E, Section 2.4.

U.S. EPA (2002a). State of the Practice for Bioreactor Landfills. U.S. EPA 625/R-01/012; U.S. EPA: Cincinnati, Ohio.

U.S. EPA (2002b). Assessment and Recommendations for Improving the Performance of Waste Containment Systems. EPA/600/R-02/099, USEPA ORD, Cincinnati OH, USA, December 2002.

U.S. EPA (2003a). Municipal Solid Waste, Generation, Recycling, and Disposal in the United States; Facts and Figures for 2003, U.S. EPA 530/F-05/003; U.S. EPA: Washington, DC.

U.S. EPA (2003b). Landfills as Bioreactors: Research at the Outer Loop Landfill, Louisville, Kentucky. First Interim Report, U.S. EPA 600/R-03/097; U.S. EPA: Cincinnati, Ohio.

U.S. EPA (2004). Monitoring Approaches for Landfill Bioreactors, U.S. EPA 600/R-04/301; U.S. EPA: Cincinnati, Ohio.

U.S. EPA (2005). Measurement of Fugitive Emissions at a Bioreactor Landfill, U.S. EPA 600/R-05/096; U.S. EPA: Washington, DC.

U.S. EPA (2005). First-Order Kinetic Gas Generation Model Parameters for Wet Landfills, U.S. EPA 600/R-05/072; U.S. EPA: Washington, DC.

U.S. EPA (2005b). Example Moisture Mass Balance Calculations for Bioreactor Landfills, U.S. EPA 456/R-05/004; U.S. EPA: Research Triangle Park, North Carolina.

U.S. EPA (2006a). www.epa.gov/reg3wcmd/solidwastesummary.htm. Accessed 6/30/2006.

U.S. EPA (2006b). http://www.epa.gov/eogapti1/module2/review2.htm. Accessed 6/28/2006.

Wang, Y., Byrd, C., and M. Barlaz (1994). "Anaerobic Biodegradability of Cellulose and Hemicellulose in Excavated Refuse Samples using a Biochemical Methane Potential Assay." Journal of Industrial Microbiology, 13: 147-153.

Wu, B., Taylor, C., Knappe, D., Nanny, M., and M. Barlaz (2001). "Factors Controlling Alkylbenzene Sorption to Municipal Solid Waste," Environmental Science & Technology 35(22): 4569-4576.

Yamaguchi, M., Minami, K., Tanimoto, Y., K. Okamura (1989). "Effects of Volatile Fatty Acids on Methanogenesis of Methanol and of Pregrowth with Methanol on Acetate Utilization by Methanogens." Journal of Fermentation Bioengineering: 68: 428-432.

Zoetemeyer, R.; Matthijsen, A.; Cohen, A.; and C. Boelhouwer (1982). "Product Inhibition in the Acid Forming Stage of the Anaerobic Digestion Process." Water Research, 16: 633-639.