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STATE-OF-THE PRACTICE REVIEW OF BIOREACTOR LANDILLS

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Notice

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Forward

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Sally Gutierrez, Director
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Abstract

Recently approved regulations by the US Environmental Protection Agency (US EPA) give approved states the power to grant landfill variance under Subtitle D by allowing these landfills to introduce bulk liquids into the solid waste mass. These type of landfills are called bioreactor landfills. The study presented here examines six full-scale bioreactor projects with the objective of providing a perspective of current practice and technical issues that differentiate bioreactor landfills from conventional landfills. For the purpose of only this study, bioreactor landfills were defined in a broad sense as "landfills where liquids are intentionally introduced into the waste mass in an effort to degrade the waste in a controlled fashion". The definition presented here includes landfills recirculating leachate with the intention of enhancing degradation as well as landfills controlling liquids and gases in a manner intended to optimize degradation.

The analysis showed that bioreactor landfills operate and function in much the same manner as conventional landfills, with designs similar to established standards for waste containment facilities. Recirculation of leachate also appeared to have little effect on the integrity or the performance of the containment system. Leachate generation rates, leachate head on the liner, leachate temperatures, and liner temperatures appeared to be essentially the same in bioreactor and conventional landfills. Data from leakage detection systems also indicated liners used for bioreactors were discharging liquid no different from that discharged by conventional landfills.

A definitive assessment regarding the effectiveness of degrading waste using current bioreactor operations was not possible, although analysis of gas data indicates that biodegradation probably was accelerated at one or two sites. This does not imply that waste was not being degraded at an accelerated rate at bioreactor landfills. Rather, ambiguities in the data precluded definitive inferences regarding the effect of bioreactor operations on waste degradation and methane generation. More detailed and carefully collected data are needed before reliable conclusions can be drawn.

Analysis of leachate quality data showed that bioreactors generally produce stronger leachate than conventional landfills during the first two to three years of recirculation. However, after two to three years, leachate from conventional and bioreactor landfills were similar, at least in terms of conventional wastewater parameters (BOD, COD, pH). The exception was ammonia, which tended to remain elevated in bioreactor landfills due to the absence of biological mechanisms for removing ammonia under anaerobic conditions. Analyses were not conducted to determine if bioreactor operations affect concentrations of metals, volatile organic compounds, or other constituents in leachate.

Settlement data collected from two of the sites indicate that settlements were larger and occurred at a faster rate in landfills operated as bioreactors. Anecdotal reports and visual observations at the other sites were consistent with the settlement data. Thus, the waste mass in a bioreactor can be expected to settle more quickly than in a conventional landfill. However, the results were inconclusive about the nature of the settlement primary, caused by the increase in the mass by the liquid introduced, or secondary, caused by an increase in degradation of solid waste mass.

An important finding of this study is that insufficient data are being collected to fully evaluate whether bioreactor methods used in practice at commercial and municipal landfills are effective in enhancing waste degradation, stabilization, and gas generation. Future studies should include more detailed monitoring and evaluation schemes that can be used to form definitive conclusions regarding the effectiveness of bioreactor operational methods. Data from such studies would also be useful in identifying more efficient and effective methods for operating bioreactor landfills.

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Acknowledgment

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1.0 Introduction

Conventional municipal solid waste (MSW) landfills designed and operated in accordance with the technological principles described in Subtitle D of the Resource Conservation and Recovery Act (RCRA) (40 CFR Part 258) generally employ systems that minimize the amount of moisture entering and retained in the waste. The intent of these systems is to minimize the risk of groundwater pollution by limiting the amount of leachate and gas being generated. This design and operation philosophy also results in decomposition of buried waste at suboptimal rates for decades, and perhaps even centuries. As a result, leachate and gas generation may persist long into the future (albeit at low rates), resulting in the need for long-term management and monitoring of landfills. This long-term requirement complicates defining a period for post-closure care (Barlaz et al. 2002a), and is inconsistent with the nominal 30-yr period suggested in Subtitle D.

The need for long-term monitoring and maintenance my possibly be reduced if the rate of decomposition is accelerated to a point where the stabilized solid waste does not pose an unacceptable risk to human health and the environment. The most common method to enhance the decomposition of MSW is to add supplemental water to the waste and/or to recirculate leachate, as was first proposed in the 1970s (Pohland 1975). Additional moisture stimulates microbial activity by providing better contact between insoluble substrates, soluble nutrients, and microorganisms (Barlaz et al. 1990). Today, MSW landfills that are operated to enhance waste decomposition by liquid addition and leachate recirculation are often referred to as "bioreactor landfills."

Interest in the bioreactor approach was tepid initially due to concerns regarding the effectiveness of landfill lining systems and aversion to leachate production, which was a key source of groundwater contamination in pre-Subtitle D landfills. However, great strides have been made in landfill lining technology since the 1970s and modern composite liners used for landfills limit leakage to miniscule amounts when properly installed (Bonaparte et al. 2002, Foose et al. 2001). Consequently, the introduction of water and/or recirculating leachate is now considered plausible and desirable (Pacey et al. 1999). Moreover, the accelerated decomposition associated with addition of water and/or recirculation of leachate is expected to lower long-term risks (Reinhart et al. 2002).

In addition to possible long-term risk reduction, there are several potential advantages to the bioreactor approach to landfilling (Barlaz et al. 1990, Reinhart and Townsend 1997, Pohland and Kim 1999). Enhanced decomposition increases the rate of settlement (Edil et al. 1990, El-Fadel et al. 1999, Hossain et al. 2003), which provides the landfill owner with additional airspace prior to closure (i.e., a greater mass of waste can be buried per unit volume of landfill) and limits the potential for settlement-induced damage of the final cover (Benson 2000). The accrual of air space has societal benefits as well, because more effective use of permitted capacity results in a reduction in total land use for landfills. Enhancing the rate and extent of decomposition also increases the rate of landfill gas production (Klink and Ham 1982, Findikakis et al. 1988, Barlaz et al. 1990, Mehta et al. 2002), improving the viability of gas-to-energy options. Recirculating leachate through the waste can also reduce leachate treatment costs (Pohland 1975, 1980, Reinhart et al. 2002).

Over the last two decades there have been a variety of studies of the bioreactor process (Townsend et al. 1996, Reinhart and Townsend 1997, Pohland and Kim 1999, Knox et al. 1999, El-Fadel et al. 1999, Mehta et al. 2002) and during the last five years a number of full-scale bioreactor operations have been implemented in the US (Reinhart et al. 2002). This report describes a study in which data from six-full scale bioreactor landfill projects were analyzed. The objective was to provide a perspective of current practice and technical issues that differentiate bioreactor landfills from conventional landfills. In the context of this report, MSW bioreactor landfills are specifically defined as "MSW landfills where liquids are intentionally introduced into the waste mass in an effort to degrade the waste in a controlled fashion." This definition is similar to, but broader than the definition used by the Bioreactor Committee of the Solid Waste Association of North America (SWANA), which is "a bioreactor landfill is a controlled landfill or landfill cell where liquid and gas conditions are actively managed in order to accelerate or enhance biostabilization of the waste."

The remainder of this report is divided into six sections. Section 2 provides a review of regulatory issues related to bioreactor landfills in the United States. Both federal and state regulatory issues are reviewed in Section 2. Methods used to select the sites that were studied are described in Section 3 and general characteristics of each site are described in Section 4. Section 5 describes operational characteristics of each facility (leachate volumes, recirculation rates, settlements) and Section 6 describes the impacts that bioreactor operations are having on properties of the waste, the volume of gas, and the composition of the leachate. In Sections 5 and 6, emphasis is placed on comparisons between bioreactors and conventional MSW landfilling. Conclusions and recommendations are presented in Section 7.

2.0 Regulatory Overview

RCRA's Subtitle D Criteria for MSW Landfills (40 CFR part 258; 56 FR 50978), was promulgated on October 9, 1991. These criteria establish minimum performance standards for the siting, design, operation, and post-closure management of landfills that receive non-hazardous solid waste. These regulations were developed because landfills that receive non-hazardous solid waste have the potential to result in groundwater contamination and problems associated with gas migration. When developing Subtitle D, the United States Environmental Protection Agency (USEPA) recognized the potential advantage of leachate recirculation and allowed recirculation of leachate at landfills that were constructed with a liner specified in the regulations (a composite liner consisting of 0.61 m of clay having hydraulic conductivity ≤ 10-7 cm/s overlain by a geomembrane) and a leachate collection and recovery system (LCRS).

Subtitle D of RCRA set forth minimum standards for landfill design and operation. The administration of Subtitle D was largely delegated to the states, which can develop more restrictive regulations. In fact, some states (i.e., New York and Pennsylvania) require double composite liners. Thus, while leachate recirculation was permitted under Subtitle D, the actual approval of applications for permits to operate landfills as bioreactors was left to each state. There has been much discussion and debate whether sites with an alternative liner design are allowed, under Subtitle D, to recirculate leachate.

Recently, there have been three developments that have affected the permitting and operation of bioreactor landfills including (i) Project XL, (ii) the Research, Development, and Demonstration (RD&D) rule, and (iii) requirements for gas collection at bioreactor landfills. The US EPA implemented Project XL to facilitate the use of superior technology more quickly. Permits for innovative and superior technologies are to be processed rapidly with input from USEPA. To date, four bioreactor landfill projects have been approved as part of Project XL. These projects eventually will provide additional data on specific aspects of bioreactor landfills including issues related to the introduction of supplemental liquids to landfills and leachate recirculation in landfills with alternative liners. However, the length of time required to obtain permits remains an obstacle to the progression of bioreactor technology.

In June 2002, USEPA issued a notice of proposed rule making entitled "Research, Development, and Demonstration Permits for Municipal Solid Waste Landfills" (Federal Register, June 10, 2002, 40 CFR Part 258, Research, Development, and Demonstration Permits for Municipal Solid Waste Landfills, EPA Proposed Rule), commonly referred to as the "RD&D" rule. The proposed RD&D is designed to add flexibility to the existing Subtitle D rule to allow landfill owners to document that alternate approaches to design and operation of landfills may result in improved economics and/or environmental performance. The proposed RD&D rule allows states to waive specific provisions of the MSW landfill criteria, including (i) operating criteria (except procedures for excluding hazardous waste and explosive gas control in Subpart C), (ii) design criteria in Subpart D, and (iii) final cover criteria in section 258.6 a & b. The proposed rule would allow alternate designs which might incorporate improvements in areas such as (i) liner system design and materials, (ii) leachate drainage and recirculation system design and materials, (iii) the addition of supplemental water to accelerate decomposition, and (iv) new liquid distribution techniques. Other innovative developments potentially are eligible too.

The RD&D permits would be issued with an initial 3-year term, with three optional 3-year extensions, for a total of 12-years. The proposed rule specifies that annual reports be submitted for all RD&D permits granted under this program. These annual reports would summarize data obtained during the year and assess progress towards the goals of the specific RD&D program at a site.

Under the proposed rule, states could approve permits to allow the addition of non-hazardous liquids to a landfill unit constructed with an alternative liner (i.e., a liner that complies with the performance design criteria in 40 CFR 258.40(a)(1) rather than a liner that complies with the material requirements in 40 CFR 258.40(a)(2)). The State Director must be satisfied that a landfill operating under an RD&D permit will pose no additional risk to human health and the environment beyond that which would result from the current MSW landfill operating criteria. Under the RD&D rule, permitting would still be at the discretion of each state. In essence, the RD&D rules gives each state authority to permit bioreactor landfills that might not have been permitted under Subtitle D alone.

The US EPA issued a final rule on National Emissions Standards for Hazardous Air Pollutants (NESHAPS) for landfills in January 2003 (Federal Register, January 16, 2003, 40 CFR Part 63, National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills, EPA Final rule). Included in this rule are Maximum Achievable Control Technology (MACT) regulations that affect bioreactor landfills. Bioreactors are defined to include those landfills that add liquid, other than leachate and gas condensate, to reach a minimum average moisture content of at least 40% by weight to accelerate anaerobic biodegradation of the waste. Aerobic landfills are not included in this definition.

The rule requires that landfill gas collection and control systems begin operation within 180 days after initiating liquids addition, or within 180 days after the landfill moisture content reaches 40% by weight, whichever is later. This rule applies only to bioreactor cells that receive liquids other than leachate and that have a design capacity greater than 2.5x106 Mg or 2.5x106 m3. Affected sites will be required to submit startup, shutdown, and malfunction plans, and to track and report every six months any deviations from air pollution limits.

In summary, the operation of landfills with leachate recirculation has always been permitted under Subtitle D, whereas addition of liquids other than leachate and gas condensate has not been permitted. The addition of such liquids could be permitted under the proposed RD&D rule. In all cases, whether a traditional Subtitle D permit, a Project XL application, or an application under the RD&D rule (after its promulgation), the ultimate authority to permit the construction and operation of landfills will rest with the states. The approach of the states has varied considerably, although many states have become more receptive to the operation of landfills as bioreactors.

3.0 Sites Selection and Data Collection

3.1 Selection Process

The intent of the site selection process was to identify six MSW landfills that are representative of the state-of-the-practice regarding bioreactor landfill operations and where a review of data and operations was possible. All possible potential sites were identified by reviewing the literature, contacting private solid waste management companies, contacting various leaders in the solid waste industry, and reviewing lists of current bioreactor landfill operations prepared by SWANA and the US EPA. More than 100 potential sites were identified through this process. Of these sites, 12 were identified that as suitable for further consideration. This initial screening, in which 88 sites were eliminated, was based on the length of time that the site was in operation, the available monitoring data, the site location, the perceived interest in the site owner in participating, and the likelihood that the data would not otherwise be published.

Each of the 12 sites was examined to determine its suitability for the study through a series of three criteria. The first criterion was whether the site owner would participate (i.e., by providing interviews and data, and allowing site visits) and permit public disclosure of data provided to the investigators. The second, only full-scale sites being operated with the intent of enhancing decomposition were included (e.g., pilot studies and sites recirculating leachate solely to eliminate or reduce leachate treatment were not included). The third, sites were sought that represent the range of conditions encountered in North America (i.e., diversity in regulations, locations, climate, waste characteristics, design, operational methods, and ownership). Sites with a longer operational period (as a bioreactor) and/or modern instrumentation were considered more suitable as well.

All of selected sites (Table 1) were located in the eastern half of North America. Efforts were made to include landfill sites in the western states and in dry climate, however no sites meet the selection criteria established earlier. The locations range from southeastern to upper midwestern with climates ranging from warm and humid (Site W) to wet and seasonal with severe winters (Site C). The sites received MSW from a variety of sources including residential, light industry, and construction and demolition activities. One of the sites is aerated with the intention of promoting aerobic decomposition (Site W), whereas all others are anaerobic. Site Q in particular was designed and operated for leachate recirculation and gas collection with the intention of promoting decomposition and stabilization of the waste. Half of the sites are privately owned. Nearly all of the sites operated as conventional Subtitle D MSW landfills for some period, either intentionally or while permitting approvals or other issues were being resolved. Bioreactor landfills that were designed as bioreactor since conception used a horizontal liquid introduction system since that type of system lends itself for such practices. The only retrofit site (site W), on the other hand, used utilized vertical injection wells. Directional drilling in landfills is rather problematic as a result it is expected that most retrofit bioreactor landfills would employ vertical injection wells.

3.2 Data Collection, Analysis, and Quality Evaluation

After the six sites were selected, a representative from each site was contacted and requested to provide information regarding the design, operation, and monitoring of the bioreactor landfill. When available, this information was reviewed before the site visit to identify data gaps and additional questions to be addressed on site. The data were entered into site characterization forms, which summarize the information evaluated for each site.

Site visits were conducted between May and August 2002, during which one or more technical points of contact were interviewed at each site. Additional information (annual reports, permit documents, design reports, and operating data) was reviewed and entered into the site characterization forms during the visits as appropriate. Copies of pertinent reports and other sources of information were also reviewed and copied for use in subsequent analyses. Results of these analyses were compiled in site summary reports.

A single reviewer evaluated data quality to ensure consistency. The most reliable sources of information were documentation from regulatory agencies, design documents certified by a professional engineer, and reports to regulatory agencies (rank = 1 on the site characterization forms). Personal observations and information that could be traced to original verifiable data sources were also given the highest quality ranking. Other design and operating documents, and data traced to original sources where data quality could not be fully determined, were ranked lower (rank = 2). Information provided verbally, and data from sources where data quality could not be determined, were given the lowest ranking (rank = 3). The data quality evaluation was subjective. However, because one person performed the evaluation using pre-determined quality criteria, the relative data quality rankings are believed to provide reliable metrics of data quality.

4.0 General Site Characteristics

4.1 Waste Stream

Characteristics of the waste streams and placement methods are summarized in Table 2 for the six landfills that were studied. Each of the landfill had a diverse waste stream, and the rate of landfilling varied from 27,200 to 848,000 Mg/yr. Residential and light industrial refuse comprised the majority of the waste while other landfilled wastes depended on the local industries in the vicinity of the landfill. For example, shredder fluff from automotive recycling was a significant waste stream for Sites Q and E, whereas foundry sand was a significant waste stream at Site E. Nearly all of the sites accepted construction and demolition waste as well. In general, a wide variety of wastes were accepted at each landfill, which is similar to most landfills that operate in a conventional manner. Site E could be considered an exception, because residential and light industrial refuse only comprise about 50% of the waste stream at this site.

Conventional waste placement methods were used at all sites (Table 2). Waste was generally discharged at the working face from trucks, spread into lifts approximately 3 m thick, although thinner lifts were used at Sites D and E. Heavy-footed compactors typically used in conventional landfills were being used to

Table 1: General Characteristics of MSW Landfill Sites Selected for the Study

Site	Region	Owner	Average Annual Precipitation (mm)	Bioreactor Active Area (ha)	Bioreactor Duration (year)	Design Type	Anaerobic or Aerobic	Implementation Method	Gas Collection
S	Upper Midwest	Private	670	3.6	8	Recirculation with horizontal piping	Anaerobic	As-Built	Active
D	East	State	1041	9.7	2	Recirculation with horizontal piping	Anaerobic	As-Built	Active
Q	Northeast	Private	940	12.1	1	Bioreactor with horizontal piping	Anaerobic	As-Built	Active
W	Southeast	County	1200	2.4	2	Bioreactor with vertical wells	Aerobic	retrofit	Passive
C	Upper Midwest	County	762	5.6	4	Recirculation with horizontal piping	Anaerobic	As-Built	Passive
E	Upper Midwest	Private	838	17.8	4	Recirculation with horizontal piping	Anaerobic	As-Built	Active

Notes: 1 in = 25.4 mm, 1 ac = 0.405 ha

Table 2: MSW Waste Stream Characteristics and Placement Methods

Site	Rate of Landfilling (Mg/Year)	Waste Stream	Filling Method	Daily Cover	Average Waste Thickness
S	116,000	Residential and light industrial waste, demolition waste, non-hazardous industrial waste.	Conventional filling with heavy compactor in 3 m lifts.	Sand, crushed glass, tarps. Removed and reused daily. Soil-like cover ~ 150-300 mm thick.	24
D	109,000	Residential and light industrial waste, non-hazardous industrial waste, construction and demolition waste.	Spread in thin (1 m) lifts, compacted with heavy compactor .	Soil, tarps, and shredded C&D waste (foam was used previously).	24
Q	848,000	Residential, commercial and institutional waste, construction and demolition waste, ash, shredder fluff, biosolids, contaminated soil.	No information.	Contaminated soil, silty sand, spray-on mulch (cement, water, shredded paper). No removal.	20
W	27,200	Residential and light commercial waste	Spread in thin lifts and compacted with a bulldozer.	Local soils, thickness up to 1 m due to regulatory concerns regarding odors.	10
C	30,800	Mixed residential and light industrial MSW, asbestos, sludges from leachate treatment.	Heavy compactor, 3 m lifts.	Local sand 150-300 mm thick and degradable spray-on mulch. No removal.	30
E	721,000	Residential waste, foundry sand, demolition debris, contaminated soils, shredder fluff, miscellaneous special wastes.	Heavy compactor in 0.6 m lifts.	Shredder fluff, foundry sand, contaminated soil, local soil. Removed and reused daily.	68 (maximum)

compact the waste at five of the six sites. The exception was Site W, where the waste was spread in thin lifts and compacted with a bulldozer. No effort was made at any of the sites to process the waste (shred, mill, homogenize, etc.) prior to placement. Consequently, the waste mass at each of the sites most likely was highly heterogeneous mixture of various types of waste. The total waste thickness varies appreciably, from 10 m at Site W to a proposed maximum thickness of 68 m at Site E.

A wide variety of materials were also used for daily cover (Table 2), as is common at conventional landfills. Porous materials such as sand and crushed glass were used at some sites, whereas thicker (0.5-1.0 m) layers of fine textured soils were used at some sites for odor control. Spray on daily cover was used at two sites (Q and C) and non-putrescible wastes (foundry sand, contaminated soils, shredder fluff) were utilized as daily cover at three sites. Only two sites (S and E) were actively removing daily cover prior to burial of additional waste to facilitate better distribution of leachate and to save airspace.

4.2 Liner System

Since all the sites examined were permitted under RCRA Subtitle D, they all used a liner system (as outlined in Figure 1) to protect groundwater from potential leachate contamination. Thus, these systems were typical of those required for conventional landfills by the regulatory agencies overseeing these sites. Each site had at least a composite liner consisting of a geomembrane overlaying either a compacted clay liner (Sites C, E, S, and W) or a geosynthetic clay liner (GCL) (Sites Q and D). A portion of the bioreactor landfill cell, at site S, was constructed on top of older pre-Subtitle D MSW landfill. As a result, the lining system for this portion employed a GCL system instead of compacted clay liner since GCLs can withstand greater distortion without cracking relative to compacted clay liners. A biaxial geogrid was also placed under the GCL at Site S to provide support if differential settlements occur in the older cell. Bottom liner systems at sties at the later two sites (Q and D) had double liners consisting of one composite liner and one geomembrane liner, with the two liners separated by a leak detection system.

Site D was required to modify or enhance the design of the lining system or the final cover because the landfill was being operated as a bioreactor. As mentioned previously, Site D was required to use a double liner (a secondary geomembrane liner beneath the upper composite liner) with a leak detection system (geocomposite drainage layer). A double liner was installed at Site Q at the owner’s discretion (regulations only required a single composite liner) to ensure that all leachate in the bioreactor would be collected. The owner of Site also indicated that installing a double liner facilitated approval of the permit to operate the bioreactor. The regulatory agency overseeing Sites C and S requires that a lysimeter (an underdrain used to collect liquid) be installed beneath the leachate collection line and sump in all landfill cells. Lysimeters at both Sites C and S were constructed using a 1.5-mm-thick high-density polyethylene geomembrane overlain by a geotextile, and were backfilled with gravel. To date, none of these lysimeters has shown higher than anticipated leakage rates or contaminant levels.

Schematics of the cover systems used at the six sites are shown in Figure 2. As with the lining systems, the final covers were typical of those required for conventional MSW landfills operating under RCRA Subtitle D. However, as of the date of this report, none of the sites had completed final closure. Final cover had been placed on only a small portion of the landfill (sideslopes) at only two sites (Sites C and S). Thus, the cover profiles shown in Figure 2 may not reflect the final cover that is ultimately placed at each site.

Four of the sites are planning for a final cover incorporating a geomembrane, but only one (Site E) has planned for a composite barrier layer in the final cover. The proposed final cover system at two of the sites (Sites Q and W) rely only on compacted clay as the barrier layer, even though the bottom liner systems at both sites employ geomembranes. The regional authority where Site Q is located support the use of relatively permeable final covers (e.g., covers without geomembranes, densely compacted clay barriers, and/or GCLs) with the intention of reducing the contaminating lifespan of the landfill by promoting percolation into the waste.

4.3 Leachate Collection System

Characteristics of the leachate collection systems are shown in Figure 1 and are summarized in Table 3. Crushed stone or pea gravel were used as the primary component of the leachate collection layer at three

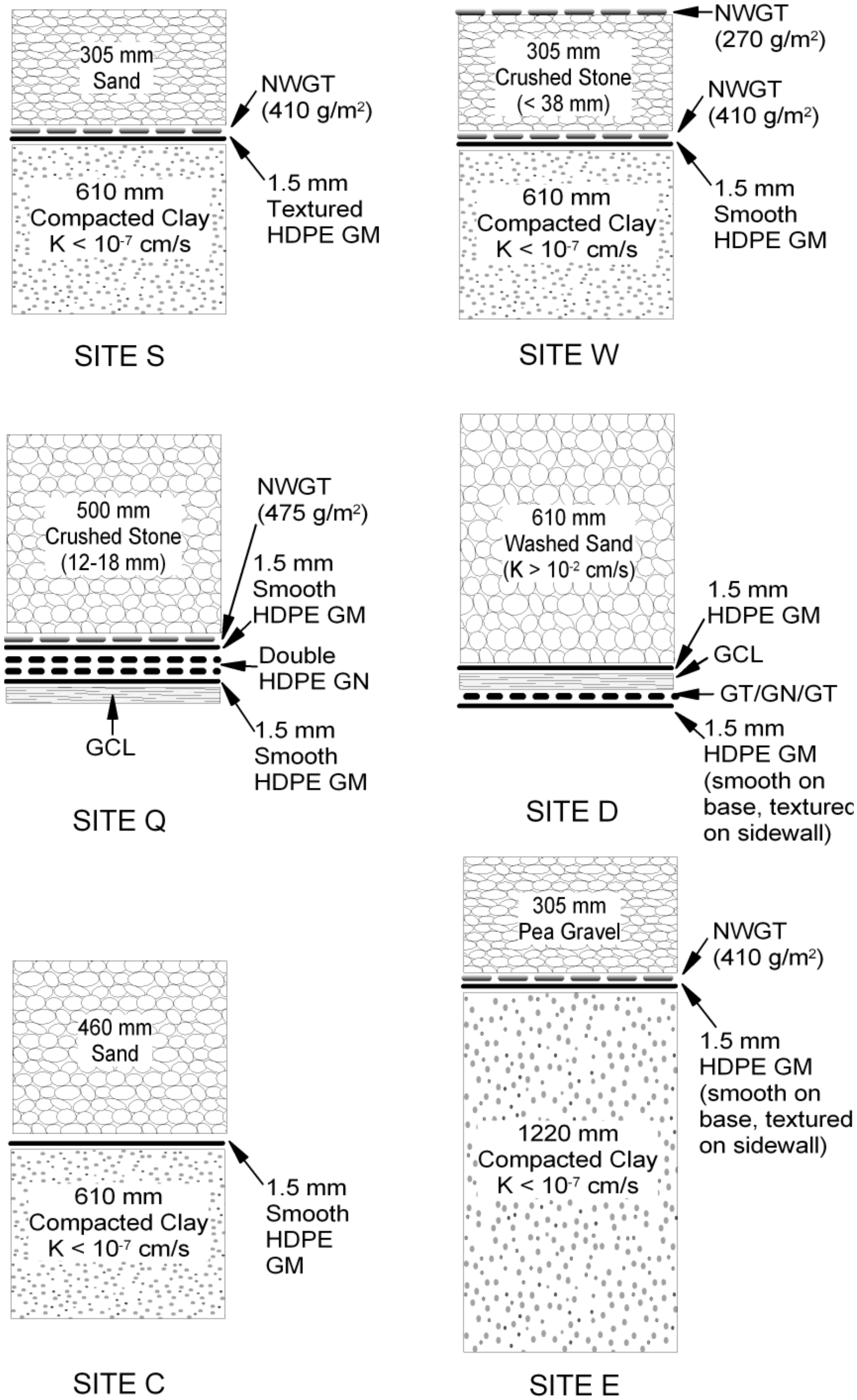


Figure 1: Schematic profiles of lining systems

NWGT = non-woven geotextile, GM = geomembrane, GN = geonet, GT/GN/GT = geocomposite of geonet with geotextiles bonded to each side, GCL = geosynthetic clay liner, HDPE = high density polyethylene, K = saturated hydraulic conductivity. 1 in = 25.4 mm.

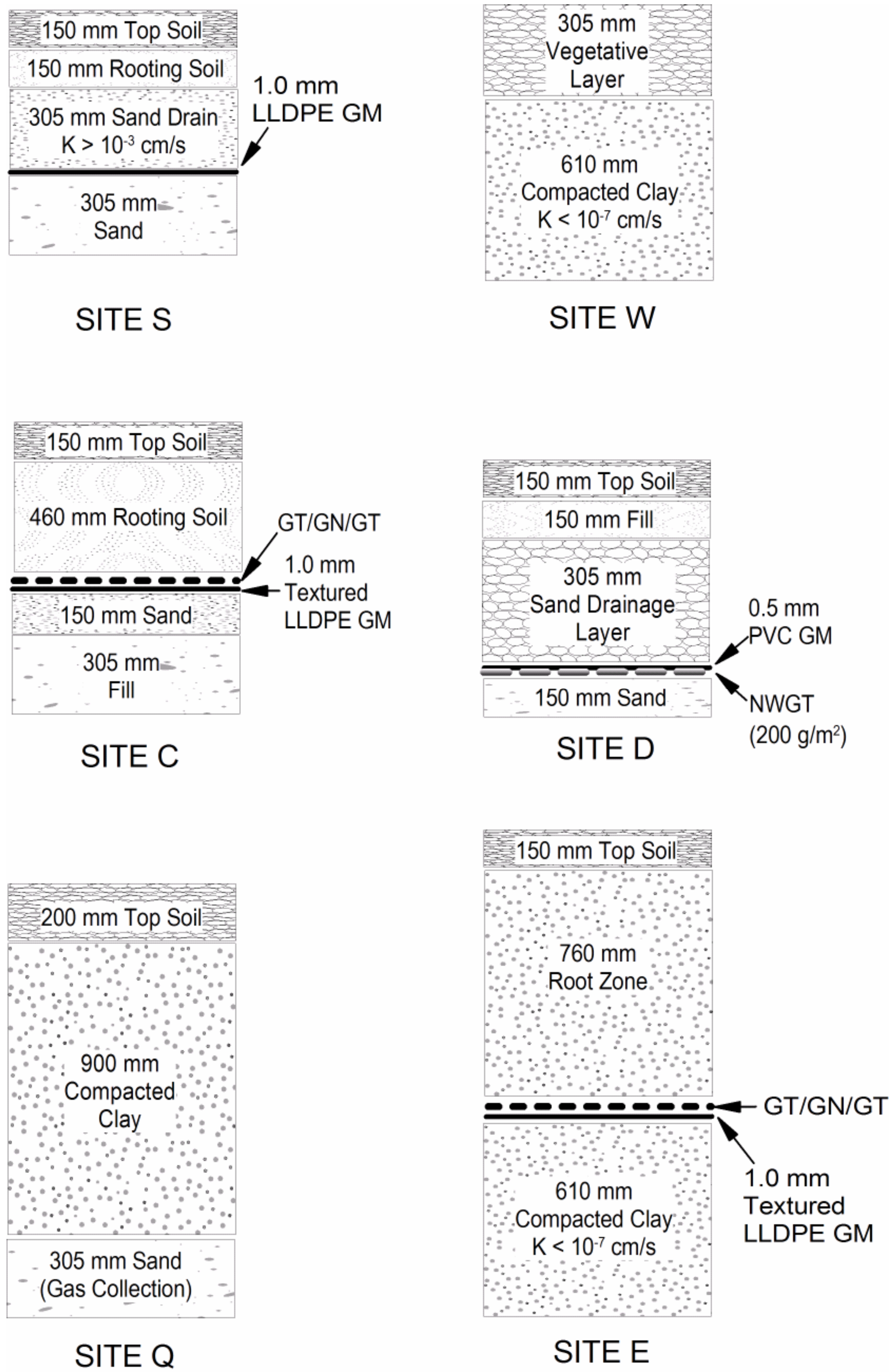


Figure 2: Schematic profiles of cover systems

NWGT = non-woven geotextile, GM = geomembrane, GT/GN/GT = geocomposite of geonet with geotextiles bonded to each side, LLDPE = linear low density polyethylene, K = saturated hydraulic conductivity. Sand layer under geomembrane at Site D is a bedding layer. 1 in = 25.4 mm.

Table 3: Characteristics of Leachate Collection System

Site	Drainage Layer[a]	Collection Pipes	Removal Method	n Frequenc	Disposition
S	305 mm sand (hydraulic conductivity ≈ 10^{-2} cm/s) with 12-38 mm gravel pack around pipes. NWGT separator between gravel and sand.	One SDR 11 150-mm HDPE pipe per cell (≈ 50 m spacing) with 12 mm holes spaced at 150 mm.	From sump via conventional submersible leachate pump and sideslope riser.	As needed based on level in sump.	Pumped to equalization tank. Shipped to off-site POTW if not recirculated.
D	600 mm washed sand (hydraulic conductivity ≈ 10^{-2} cm/s); washed gravel meeting 38 to 62 mm stone, wrapped with a woven monofilament polypropylene fabric.	SDR17 150 mm HDPE pipe spaced at 30 m. 12 mm perforations spaced at 150 mm.	From sump via conventional submersible leachate pump and sideslope riser.	As needed based on level in sump.	Pumped to storage tank. Shipped to off-site POTW if not recirculated.
Q	500 mm crushed stone (12-18 mm).	SDR 11 150 or 200 mm HDPE perforated pipe spaced at 30 m. 13 mm perforations with 100 mm spacing.	From sump via conventional submersible leachate pump and sideslope riser.	As needed based on level in sump.	Directly pumped into leachate recirculation lines. On-site treatment plant available if recirculation is not available.
W	305 mm of 38-mm crushed stone overlain by 270 g/m^2 NWGT.	None	From sump via submersible leachate pump and collection manhole.	As needed based on level in sump.	Pumped to equalization tank for recirculation.
C	305 mm sand (hydraulic conductivity ≈ 10^{-2} cm/s) with gravel pack around pipes. NWGT separator between gravel and sand.	One SDR 11 150-mm HDPE pipe per cell (≈ 60 m spacing) with 12 mm holes spaced at 150 mm.	Leachate flows by gravity from sump to vault via pipeline passing through the liner sidewall.	Continuous	Stored in vault prior to pumping for recirculation. Excess leachate treated in on-site pretreatment ponds and then land applied to cover on closed cell of adjacent landfill.
E	305 mm of 9-19 mm pea gravel with hydraulic conductivity ≥ 10^{-2} cm/s;	SDR 9 150-mm HDPE pipes spaced at 50-60 m. 12 mm perforations mm holes spaced at 150 mm.	From sump via conventional submersible leachate pump and sideslope riser.	As needed based on level in sump.	Pumped directly to recirculation system or to storage tank and hauled off-site to POTW.

Notes: [a]NWGT = non-woven geotextile, 1 in = 25.4 mm, 1 oz/yd^2 = 33.9 g/m^2, 1 ft = 0.305 m sites (Sites E, Q, and W) to promote rapid flow of leachate and reduce the potential for biological fouling. Medium grain sand was used at other three sites examined (Sites C, S and D) for the leachate collection layer as well as imbedding the leachate collection lines in gravel at these sites. Generally the granular drainage material was required to have a hydraulic conductivity ≥ 10^{-2} cm/s. All of the drainage materials met this requirement, with those constructed with crushed stone or pea gravel being much more permeable than required. Geotextile was used on top of the leachate collection layer at one site. None of the leachate collection layers had special requirements stipulated by the regulatory agency beyond those for conventional MSW landfills.

The leachate collection lines used at each site were typical of those used at conventional landfills (e.g., perforated HDPE pipe). At five of the sites, liquid was removed from the sump using a conventional leachate pump deployed through a sideslope riser (Sites C, E, Q, and D) or manhole (Site W). In general, a level-sensing switch activated the pump, and leachate was pumped to an equalization tank or directly to leachate recirculation lines. The exception is Site C, where leachate flowed by gravity pipeline through a liner penetration and into a vault. Leachate at that site was then pumped from the vault by a force main to the leachate recirculation system or to lagoons for treatment.

A summary of characteristics of the recirculation systems is shown in Table 4. Leachate derived from the leachate collection system or as contaminated runoff was the only liquid recirculated at five of the six sites. Site W also recirculated uncontaminated storm water along with leachate in an effort to increase the moisture content of the waste to optimum levels. Five of the six sites used horizontal distribution lines buried in trenches filled with gravel or tire chips. In addition to recirculating leachate through horizontal distribution lines, Site C also applied leachate on the working face and on the top deck of one cell where waste has reached final grades. Vertical injection lines and infiltration galleries were tried and failed at Sites S and D, however, they were still being used at Site W. Anecdotal reports by most of the site owners indicate that vertical injection lines and infiltration galleries were less effective than horizontal distribution lines. Vertical injection tends were also observed to cause leachate to short circuit directly to the leachate collection system rather than percolating into the solid waste mass. Engineering changes may have been possible to overcome these shortcomings. Nevertheless, Sites S has discontinued using the vertical injection lines, and Site D only uses vertical injection lines and infiltration galleries in older cells.

The horizontal trenches were generally square or rectangular in cross-section (0.6 x 0.6 m to 1.0 x 1.5 m) and extend across the breadth of the cell. The trench spacing varied considerably depending on the site, with the horizontal spacing ranging between 15–60 m and the vertical spacing ranging between 6-11 m. Perforated or slotted high density polyethylene (HDPE) pipe 75-150 mm in diameter was the most common piping material used the distribution line. The perforations generally are paired, approximately 12 mm in diameter, and spaced at approximately 150 mm. At Site C, the spacing of the perforations decreases along the length of the pipe to promote more uniform discharge of liquid along the length of the pipe. To prevent leachate seeps, the ends of the distribution lines (10-30 m) were not perforated, and in some cases a bentonite or compacted clay plug was placed at each end of the trench to prevent leachate breakouts on the side slopes.

4.4 Landfill Gas (LFG) Collection and Management System

Four of the six sites operated active gas collection systems that were connected to a flare (Table 5). At the time of this study, all of the four sites were considering a gas-to-energy generating facility. The other two sites used passive gas vents (Site W) or passive wells (Site C). Site C was also considering installation of an active gas system and a gas-to-energy facility. Energy recovery was not an option at Site W, since it treats the solid waste aerobically thus not generating methane. Gas collection began at some sites after leachate recirculation began and prior to recirculation at other sites. For example, at Site D, regulations required that gas collection begin before recirculation.

Conventional vertical gas wells were installed by augering through the waste and used at three of the four sites with active gas systems (Sites C, E, and S) and for the passive LFG collection wells at Site C. The spacing of vertical wells varied between 45 and 100 m. Sites D and E collected gas through leachate collection pipes and horizontal leachate collection lines. Site Q used an innovative horizontal gas

Table 4: Characteristics of Liquids Recirculation/Injection Systems

Site	Source	Injection Method	Application Frequency	Metering	Automation
S	Composite leachate from bioreactor and conventional areas, contaminated runoff.	Horizontal lines at two elevations in 0.6 x 0.6 m trenches backfilled with washed stone (22 to 38 mm). Spaced at 60 m horizontal and 10 m vertical. Distributed in 100 mm HDPE slotted pipe sloped at 0.5%. 15 m at each end solid to prevent seeps	As needed based on accumulation of leachate in tank.	Weigh slips for tanker trucks	None
D	Composite leachate from bioreactor and older areas.	Horizontal lines in stone (38-64 mm)-filled trenches (0.6 m x 0.9 m). Spaced 6 m vertically and 18 m (top) to 61 m (bottom) horizontally. Distributed in 150 mm perforated pipe with 13 mm holes. 30 m at each end solid to prevent seeps. 0.9 m clay collar at each end.	-	Meter total flow	Distribution to lines is manually switched
Q	Composite leachate from bioreactor and older areas.	Horizontal lines in 1.0 x 1.0 m trench backfilled with crushed stone (12-18 mm). Spaced 6 m vertically and 20 m horizontally. Conventional HDPE 75 mm in diameter with 13 mm perforations spaced at 100 mm.	Continuous. Lines dosed sequentially, with each line being dosed approx. every 10 d.	Meter total flow and flow per line	Leachate collection and recirculation operates continuously in response to leachate level in sump. Distribution to trenches is controlled manually using valves.
W	Composite of leachate from bioreactor and older area along with storm water.	Vertical PVC wells 25 or 50 mm in diameter located on 15 m grid. 25 mm wells are screened from 1 m below surface and were installed by direct push. 50 mm wells are in clusters of 3 screened at various depths. Installed by auger and backfilled with crushed glass All wells are slotted with 40 slots/m	Variable, depends on level in equalization tank	Meter on equalization tank only	Float switch on equalization tank used to cycle leachate recirculation pump. Distribution to wells is manually switched.

Notes: [a]NWGT = non-woven geotextile, 1 in = 25.4 mm, 1 oz/yd^2 = 33.9 g/m^2, 1 ft = 0.305 m, 1 gall/ft = 12.4 L/m, 1 gall/d = 3.78 L/d. Hyphens indicate quantity could not be determined

Table 4: Characteristics of Liquids Recirculation/Injection Systems (cont.)

Site	Source	Conveyance	Injection Method	Application Frequency	Metering	Automation
C	Leachate and water in leachate treatment ponds.	Collected in vault and pumped via force mains to injection lines	Horizontal lines spaced 6 m vertical and 15 m horizontal and constructed from 100 mm and 125 mm perforated HDPE pipe (slip fit). Perforation frequency varies along pipe to achieve more uniform distribution of leachate. Sloped at 1%. Solid 15 m from each end to prevent seeps. Lines bedded in 0.6 m x 0.6 m trench filled with 150 mm tire chips.	Dose lines sequentially, with approximated 1-2 days per line to achieve target dose of 290 L/m	Flow rate during dosing is metered.	Pumps are switched based on leachate level in vault. Valving from force main to recirculation lines is manual. Valving and lines insulated and heated for winter operation
E	Composite leachate from bioreactor and older areas.	Pumped via force main to horizontal distribution lines.	Horizontal lines spaced at 11 m (approx) vertical and 32 m horizontal (average) and sloped at min. 1%. 150 mm SDR 9 HDPE pipe with 12 mm perforations spaced at 150 mm. Trench is filled with clean stone (1.5 inch) and covered with non-woven geotextile (200 g/m2). Pipe is solid 30 m from each end to prevent seeps. Bentonite plugs installed at end of each trench.	Varies, average application is 29,000 L/d in 2001.	Total flow monitored.	Leachate recirculation pump controller at leachate lift station. Manual valves for injection to distribution lines.

Notes: [a]NWGT = non-woven geotextile, 1 in = 25.4 mm, 1 oz/yd^2 = 33.9 g/m^2, 1 ft = 0.305 m, 1 gall/ft = 12.4 L/m, 1 gall/d = 3.78 L/d. Hyphens indicate quantity could not be determined

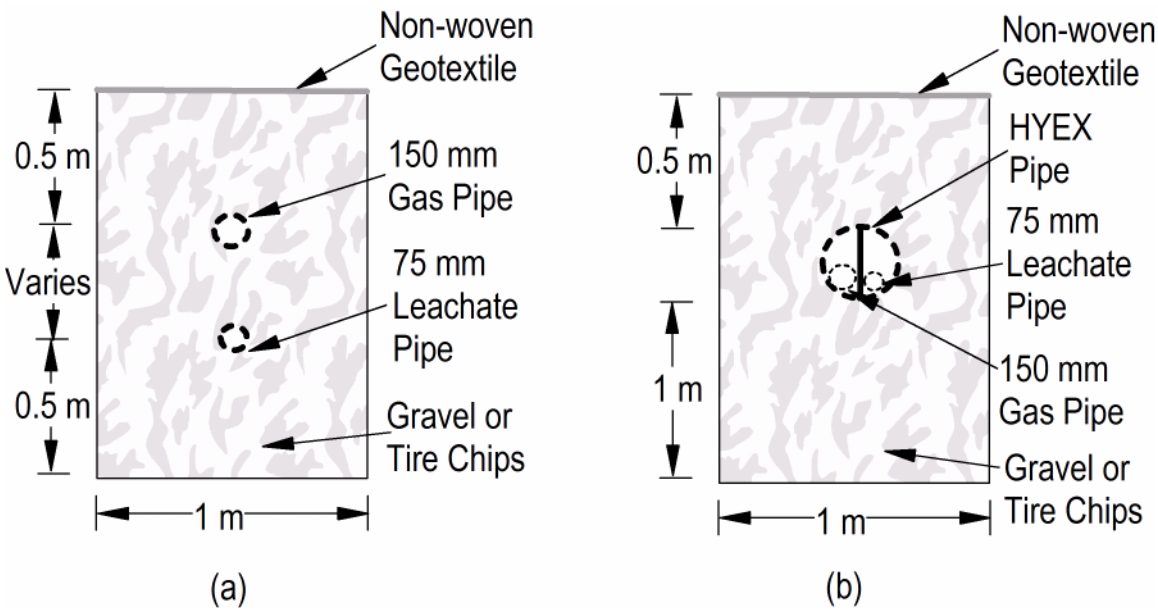


Figure 3: Schematic of horizontal trenches with co-located gas collection and leachate distribution lines: (a) stacked arrangement and (b) HYEX pipe with gas and leachate lines on interior

collection system co-located with the recirculation lines to improve the efficiency of gas collection. The recirculation and gas collection lines were either stacked or routed though a single section of perforated HYEX pipe (Figure 3). A concern with the HYEX design was that settlement damage which may result in low spots where leachate accumulates in the pipe, precluding effective gas extraction.

Generally, LFG collection was suspended in areas where the waste is receiving liquids since the introduction of leachate may temporarily block or flood the gas collection lines. For example, at Site Q, the LFG collection lines were shut down during a recirculation dose and for two days thereafter to allow the recirculated leachate to flow out of the trench. However, gas collection continues in adjacent collection lines. The HYEX design used at Site Q was theoretically designed to permit gas collection to resume sooner after dosing, and reduce the potential to damage gas wells while burying waste.

4.5 Environmental Monitoring

Monitoring programs used at each site were summarized in Table 6. Conventional monitoring systems required for regulatory compliance, including leachate monitoring, ground water monitoring, and gas monitoring were collected at all sites. Leachate and ground water monitoring included analyses for inorganic and organic contaminants along with indicator parameters at prescribed intervals. LFG monitoring generally consists of flow rate (when there is an active gas collection system), percentage of methane and carbon dioxide, and VOC concentrations. Surveys of surface emissions of VOCs had been conducted at the two sites with passive gas collection systems (Sites W and C). Only one VOC survey had been conducted at Site W, whereas periodic surveys are conducted at Site C. Methane was also monitored at Sites C, D, and E.

Systems used to monitor the physical, chemical, and biological properties of the waste vary from limited to substantial depending on the objectives of each site. More extensive monitoring systems (e.g., in situ measurements of water content, temperature, and pressure, combined with settlement measurements and periodic destructive sampling) are being used at sites interested in optimally degrading and stabilizing the waste (Sites Q and W). Relatively simple systems (e.g., settlement plates and/or aerial surveys) are being used at sites where recirculation to enhance biodegradation and settlement is the primary goal.

Table 5: Characteristics of Gas Collection System

Site	Method	Metering	Collector	Operation Frequency	Disposition of Gas
S	Active	Total extraction rate measured at flare, and metered at each well head.	Vertical gas wells spaced at 45 m and horizontal leachate recirculation lines. Well string is 200 mm perforated Sch 80 PVC with 17 mm holes at 157 holes/m. Backfilled with 38 mm rounded washed rock. Perforated from 7 m below surface of waste to 0.3 m from surface of leachate collection layer.	Continuous after recirculated leachate flows from horizontal pipes	Flare, gas-to-energy under consideration
D	Active	Total extraction rate measured at flare.	Vertical gas wells and horizontal recirculation lines.	Continuous, except horizontal recirculation lines shut off [illegible]	Flare
Q	Active	Total extraction rate measured at flare	Perforated horizontal collection pipes co-located with leachate recirculation pipes in gravel filled trenches. Gas pipe located 0.5 m above recirculation pipe. Pipe is 150 mm HDPE with 13 mm holes at 100 mm centers.	Continuous	Flare, gas-to-energy under consideration
W	Passive	None	25 mm injection wells used to passive venting.	Continuous	Atmosphere
C	Passive	Point measurements made annually with hot wire anemometer	Vertical gas wells spaced at 50 m. Well string is 200 mm slotted Sch 80 CPVC backfilled with gravel. Slots are paired, 100 mm long, 6 mm side, and spaced at 0.3 m longitudinally. Slotted from 1 m below surface of waste to 0.3 m from surface of leachate collection layer.	Continuous	Atmosphere, but active gas system with gas-to-energy under consideration
E	Active	Total extraction rate measured at flare	Vertical gas wells spaced at 100 m. Well string is perforated 150 mm Sch 80 PVC in augured hole backfilled with 25-38 mm quartz gravel. Perforated over ? to ¾ of depth of waste.	Continuous	Flare

Notes: 1 in = 25.4 mm, 1 ft = 0.305 m

Table 6: Monitoring Program Summary

Site	Waste Physical Properties	Waste Chemical and Biological Properties	Leachate	Gas	Surface Emissions	Ground Water
S	Settlements measured with settlement plates. Water content and density measured via 1 m bucket-auger sampling during installation of gas wells. Density also computed based on mass landfilled and volume consumed via aerial survey.	Volatile solids.	Temperature, pH, electrical conductivity, and depth measured weekly in the sump. Flow measured based on pumping rate from sump.	Monthly monitoring of flow and CH_4, content at each wellhead.	None	Monitoring wells and lysimeters sampled and tested as required by provincial regulation for conventional landfills.
D	In place density computed based on mass landfilled and volume consumed via ground survey.	None	Temperature, pH, electrical conductivity, and depth measured weekly in the sump. Flow measured based on pumping rate from sump. Index parameters monthly at sump and metals at collection tank	Monthly flow, CH_4, and balance gases measured at flare. 0_2, vacuum, temperature measured at well heads.	Surface monitoring for CH4 at 10 locations across cover.	Monitoring wells sampled and tested state regulation for conventional landfills.
Q	waste. Water content regularly measured using time domain reflectometry (TDR). Temperature profiles measured with thermistors and matric potential measured with thermal dissipation probes. Density computed based on mass	Lignin, cellulose, hemicellulose	Continuous monitoring of leachate depth with transducers and temperature on liner with thermocouples. Flow measured based on pumping rate from sump.	Daily monitoring of flow and CH_4, CO_2, and O_2 content at flare. Weekly measurements at each extraction line.	None	Monitoring wells sampled and tested as required by provincial regulation for conventional landfills.

Tabel6: Monitoring Program Summary (cont.)

Site	Waste Physical Properties	Waste Chemical and Biological Properties	Leachate	Gas	Surface Emissions	Ground Water
W	Settlements measured by manual survey using settlement pins. In place water content and density determined on samples collected in thin-wall sampling tubes and from drill cuttings. Weekly temperature profiles at 11 locations measured with 170 thermocouples.	Sampled by drilling on approx. semi-annual basis. Tested for volatile solids, cellulose fraction, lignin fraction.	Quarterly to semi-annual monitoring of composition, weekly monitoring of head, pH, temperature.	Random monitoring of CH_4, CO_2, and O_2 content in vent wells. Monitoring biweekly at wells within waste.	One survey conducted for organic compounds.	Analysis for inorganic and organic compounds at 7 monitoring wells as required by state regulation for conventional landfills.
C	Settlements measured by manual survey using 4 settlement plates and 8 other points. Density determined by mass landfilled and volume consumed, the latter determined by ground survey.	None	Composition based on quarterly regulatory criteria, continuous monitoring of head in sump	Monthly monitoring of CH_4 and O_2 content in LFG system, VOCs annually.	Quarterly monitoring of CH_4 and O_2 content on 30 m x 30 m grid	Analysis for inorganic and organic compounds as required by state regulation for conventional landfills
E	Settlement measured annually at settlement plates. Density determined by quarterly ground survey and mass landfilled.	None	Composition based on semi-annual and annual regulatory criteria	Quarterly monitoring of CH_4 and O_2 content, temperature; VOCs annually in LFG system and gas probes outside waste	Quarterly methane scan per NSPS requirement s	inorganic and organic compounds at 30 monitoring wells and 3 private wells as required by state regulation for conventional landfills

Four of the six sites (Sites S, C, Q, and W) measured settlements using settlement plates or other types of reference points, as well as aerial surveys. None of the settlement measurements were automated, and all of the point measurements were made using conventional land surveying methods. Density measured at all sites was based on mass landfilled and the volume consumed, and periodically by bucket augering at three sites (Sites S, Q, and W). The distribution of temperature within the waste was monitored at two sites (Sites Q and W), and in situ monitoring of water content and matric potential was conducted at one site (Site Q). Leachate temperatures were monitored at three of the sites (Sites S, Q, and W) and liner temperatures are measured at one site (Site Q). No special monitoring was required at any of the sites, except for monitoring of water quantity and quality in the lysimeters at Sites C and S.

5.0 Landfill Operations

This section describes an analysis conducted to determine if bioreactor landfill operations were affecting the landfill operations and describes the quantities of leachate being recirculated.

5.1 Leachate Treatment and Recirculation Volumes

Typical volumes of leachate being treated and recirculated annually at each site are summarized in Table 7. These volumes were reported as 'typical' because the annual rates increase or decrease from year to year, the duration of bioreactor operations at each site varied, and design modifications were made at some of the operations to permit greater recirculation of leachate. In Table 7, the volume of leachate recirculated refers to the actual volume of liquid returned to the waste, whereas the volume of leachate generated refers to leachate collected from leachate collection systems on-site (some of which are in non-recirculation cells) as well as contaminated runoff (when data were available). The volume recirculated at Site W included storm water and leachate.

Table 7: Typical leachate generation and recirculation rates

Site	Typical Leachate Volume Generated (L/yr)	Typical Leachate Volume Recirculated (L/yr)	Percentage of Leachate Treated	Approx. Leachate Treatment Savings (US$/yr)
S	3,020,600	3,020,600	0	36,200
D	5,400,900	2,008,000	63	24,100
Q	19,771,000	19,771,000	0	-
W	2,575,500	3,108,600	0	106,600
C	8,020,100	3,380,600	58	96,500
E	18,962,400	17,932,500	5	201,000

Note: 1 gall = 3.78 L. Hyphen indicates quantity could not be determined

Four of the sites have essentially eliminated leachate treatment completely (Sites E, S, Q, and W). Site E occasionally shiped leachate off site for treatment, but the leachate treated constituted only 5% of the leachate generated. Site C treated more than half of the leachate collected annually in on-site pretreatment ponds, largely because cold weather at this site precluded recirculation during the winter months. Treated leachate is spray-applied to the surface of an adjacent closed landfill when recirculation is not possible. The recirculation system at Site C was recently upgraded to prevent freezing of appurtenances, which will permit year-round recirculation in the future. Thus, the percentage of leachate treated at Site C should decrease to near zero in the future. The fraction of leachate recirculated is lower at Site D because of regulatory issues. Recirculation was prohibited in older cells at Site D that have less sophisticated liners and the owner was not yet prepared to recirculate all of the waste in the newest cell where recirculation was still permitted.

Annual cost savings were computed for each site except Site Q, for which cost data were not available. These cost savings refer only to the savings accrued by reducing or eliminating leachate treatment, and do not include costs associated with operating and maintaining the bioreactor system. The cost savings varied between $36,200 and $201,400 in 2002 US dollars, with greater savings accrued at larger sites or sites with a greater fraction of leachate being recirculated.

5.2 Leachate Generation Rate

An evaluation was conducted for Sites Q and C to determine how leachate recirculation affected the leachate generation rate. These sites were selected for evaluation because leachate volumes were recorded regularly while the landfill operated conventionally and as a bioreactor.

Leachate generation rates are shown in Figure 4 for Site Q and in Figure 5 for Site C. For Site Q, leachate data were available from three separate cells labeled A, B, and C, while Site Q had only one test cell. Both data sets indicate that leachate recirculation has had little or no effect on the leachate generation rate, and suggest that the waste continued to absorb the leachate being recirculated. The slopes of the cumulative leachate generation curves for Site Q (Figure 4) appeared to be unaffected by the onset of recirculation, and at Site C the leachate generation rate continued to decrease after recirculation began (Figure 5). A rise in the leachate generation rate for Site C is evident for the last year of the data record, but the cause of this rise is unclear. This rise could be due to recirculation or additional precipitation, both of which are higher during the last year of data record. At some point in the future, the bioreactor landfill cells will reach field capacity as a result leachate generation rate may increase drastically in future time.

Another analysis was conducted for Site S that included adjacent conventional and bioreactor landfills of nearly identical size and geometry and that have been operated under nearly identical conditions (except for recirculation of leachate) over the same period. Each landfill was divided into three nearly identical cells

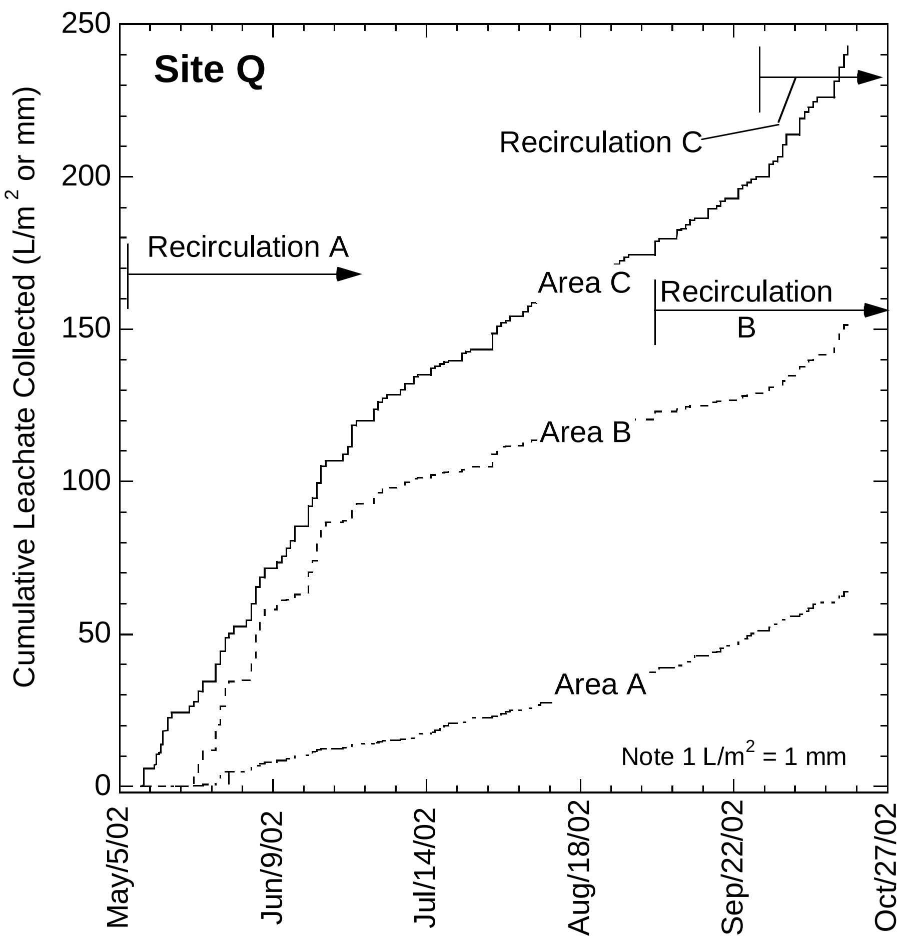


Figure 4: Cumulative Leachate Collected for Various Test Cells at Site Q Before and After Recirculation was Initiated
1 gall/ac = 1071 L/m^2, 1 in = 25.4 mm

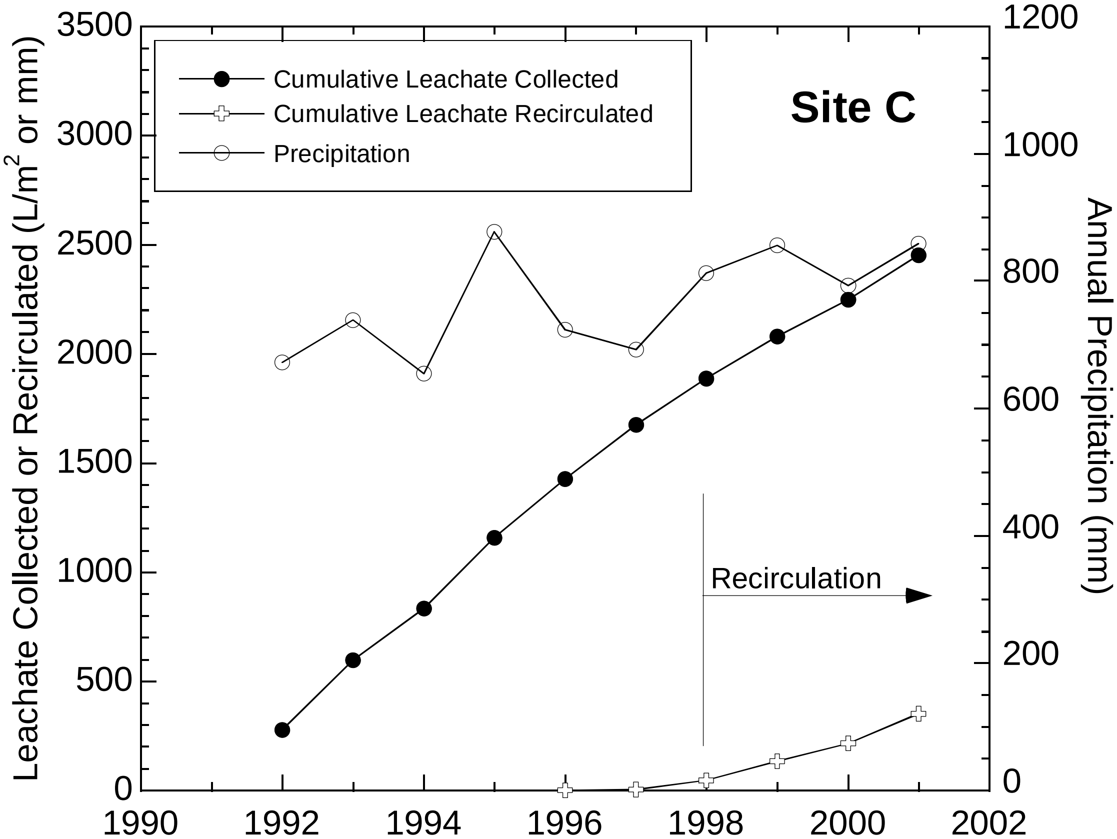


Figure 5: Annual Leachate Collected and Recirculated Along with Annual Precipitation at Site C between 1992 and 2001
1 gall/ac = 1071 L/m^2, 1 in = 25.4 mm

(numbers 2-4 in conventional landfill and 5-7 in bioreactor landfill). This data set afforded a unique opportunity for a side-by-side comparison of leachate generation rates from bioreactor and conventional operations. Leachate generation rates for Site S are further summarized in terms of box plots in Figure 6. The conventional and bioreactor landfills each have three adjacent cells. Thus, there are three box plots for each landfill operation. The central line in the box represents the median and the outer boundaries of the box represent the inter-quartile range (25th to 75th percentiles). The lines extending from the upper and lower sides of the box constitute the 5th and 95th percentiles of the data. The leachate generation rates from the bioreactor landfill cells were slightly lower than those from the conventional landfill, even though the leachate pumped from both landfills was recirculated into the bioreactor landfill along with contaminated surface runoff.

The data in Figures 4 through 6 suggest that, at least in the short term, leachate generation rates from bioreactor landfills appear no different from those from conventional landfills. Thus, in the short run, the leachate management systems in bioreactor landfills should not be taxed more severely than those in conventional landfills, at least in terms of the quantity of liquid being managed. Ultimately, a point should be reached when the waste reaches ‘field capacity’ and the leachate generation rate approximately equals the sum of the rate of recirculation and the rate of infiltration into the waste (even at field capacity, some liquid will be lost to degradation processes and evaporation through gas extraction and aeration systems). At this point, the volume of leachate to be managed will reach a maximum. The data in Figures 4 through 6 also suggest that reaching this condition may take years, at least for the recirculation rates currently being used at these sites. Moreover, a cover that limits percolation into the waste will likely be installed by the time field capacity is reached, reducing the input of additional liquid to the waste in the form of

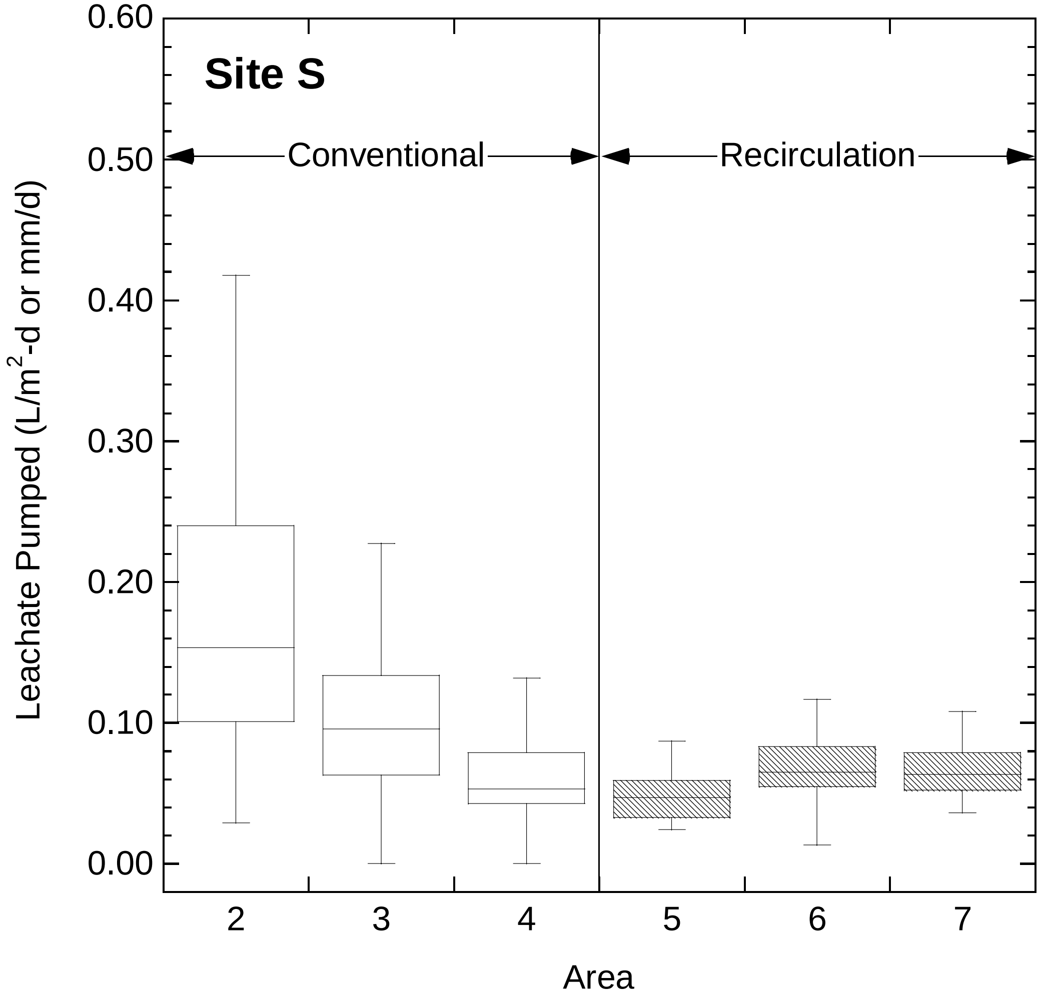


Figure 6: Box Plots Showing Leachate Volume Pumped Per Unit Area in the Conventional and Recirculation Landfills at Site S
Each landfill contains three cells (2-4 in conventional landfill, 5-7 in recirculation landfill), each with a separate sump

precipitation. Consequently, leachate collection systems in bioreactor landfills operated in a manner similar to those examined in this study may never receive greater flows than occur in conventional landfills.

5.3 Leachate Application Frequency, Dosages, and Cumulative Recirculation

The application frequency, recirculation dosage, and cumulative recirculation at each site are tabulated in Table 8. Application frequency refers to the interval between recirculation events in a particular pipe or trench. The recirculation dosage is the volume of liquid added per length of recirculation line or well during each application, and the cumulative recirculation is the total volume of liquid recirculated per mass of waste landfilled. Most sites dosed each leachate distribution line every 10 to 14 d. The application frequency depended on the availability of leachate and the level of automation. For example, Sites C, E, Q, and W employ force mains to connect an equalization tank to the recirculation lines and an automated pump (permitting more frequent application), which permits more regular dosing. In contrast, Site S hauls the leachate by truck and discharges the leachate via gravity to the leachate injection lines, which results in more intermittent dosing. Factors such as availability of leachate and weather conditions affect the application frequency at Site S. Similarly, freezing of pipes during cold weather has limited the application

Table 8: Cumulative recirculation, application frequency, and dosage for each site

Site	Total Recirculation (L/Mg waste)	Application Frequency	Dosage (L/m-pipe)		
			Typical	Maximum	Minimum
S	16.0	≈ 10 – 14 d	434	744	124
D	16.9	Varies	2.7	-	-
Q	419	≈ 10 d	870	3995	30
W	231	Daily or more often depending on leachate level in tank.	86.8 (868)	305 (3050)	1.61 (161)
C	29.2	≈ 10 – 14 d	280	474	146
E	19.1	Varies	-	-	-

Notes: 1 gall/ton = 3.9 L/Mg, 1 gall/ft = 12.3 L/m, numbers in parentheses for Site W are dosages adjusted to represent a 10-d cumulative dose. Hyphens indicate quantity could not be determined

frequency of recirculation in winter months at bioreactor landfills in cold regions (e.g., Site C), although sites in colder climates weree implementing measures (e.g., installing insulated and heated pipe networks) to permit year-round recirculation.

Liquid dosage varied considerably from bioreactor landfill site to site with the average dosage ranging from 87 to 870 L/m-pipe. The dosage at a given site may vary by more than an order of magnitude over time. The dosage depended more on operational philosophy at the site rather than the volume of waste dosed by each recirculation line. Higher dosages were used at sites operating in a mode to optimize degradation of the waste (Sites Q and W), whereas lower dosages were used at sites that are recirculating with the intention of diverting leachate while concurrently enhancing degradation and stabilization of the waste mass (Sites S, D, C, and E). This became more apparent when dosages were compared for a consistent application interval. For example, Site W applied low dosages, but did on a daily basis (or more frequently). When the dosage rate for Site W was considered as a 10-d cumulative dosage (compared to that for most other sites), then the dosage at Site W was more consistent with Site Q.

Cumulative recirculation (i.e., total amount of leachate recirculated per mass of waste) was also summarized in Table 8. The cumulative recirculation fell into two ranges, 16 to 29 L/Mg-waste and 230-420 L/Mg-waste. As was observed for the dosage, higher cumulative recirculation had occurred at sites operating in a mode to optimize degradation of the waste (Sites Q and W), whereas lower cumulative recirculation was associated with sites that were recirculating with the intention of reducing the need to treat leachate while concurrently enhancing degradation and stabilization of the waste mass (Sites S, D, C, and E).

The potential change in moisture content may be inferred from the cumulative recirculation if it was assumed that liquids were uniformly added and fully retained (i.e., no losses due to drainage, evaporation, or degradation). The low range of cumulative recirculation (16 - 29 L/Mg-waste) corresponded to a cumulative potential change in gravimetric moisture content (wet weight basis) of less than 1%, whereas the high range of cumulative recirculation (230 -420 L/Mg-waste) corresponded to a cumulative potential change in moisture content on the order of 20-40%.

5.4 Leachate Temperature and Head on the Liner

A concern regarding bioreactor operations is that reintroduction of leachate into the waste mass may raise the depth of leachate in the leachate collection system, causing additional leakage to groundwater. Another concern is that the exothermic reactions associated with biodegradation of the waste may cause temperatures adjacent to bottom liners to increase appreciably and thus causing damage to lining system components as well as leachate and LFG management appurtenances. These issues were evaluated using data collected from Sites C, Q, and S. Each of these sites was located in a cooler climate. Temperature data were not available for the sites in warmer climates, and may be different from the data from Sites C, Q, and S.

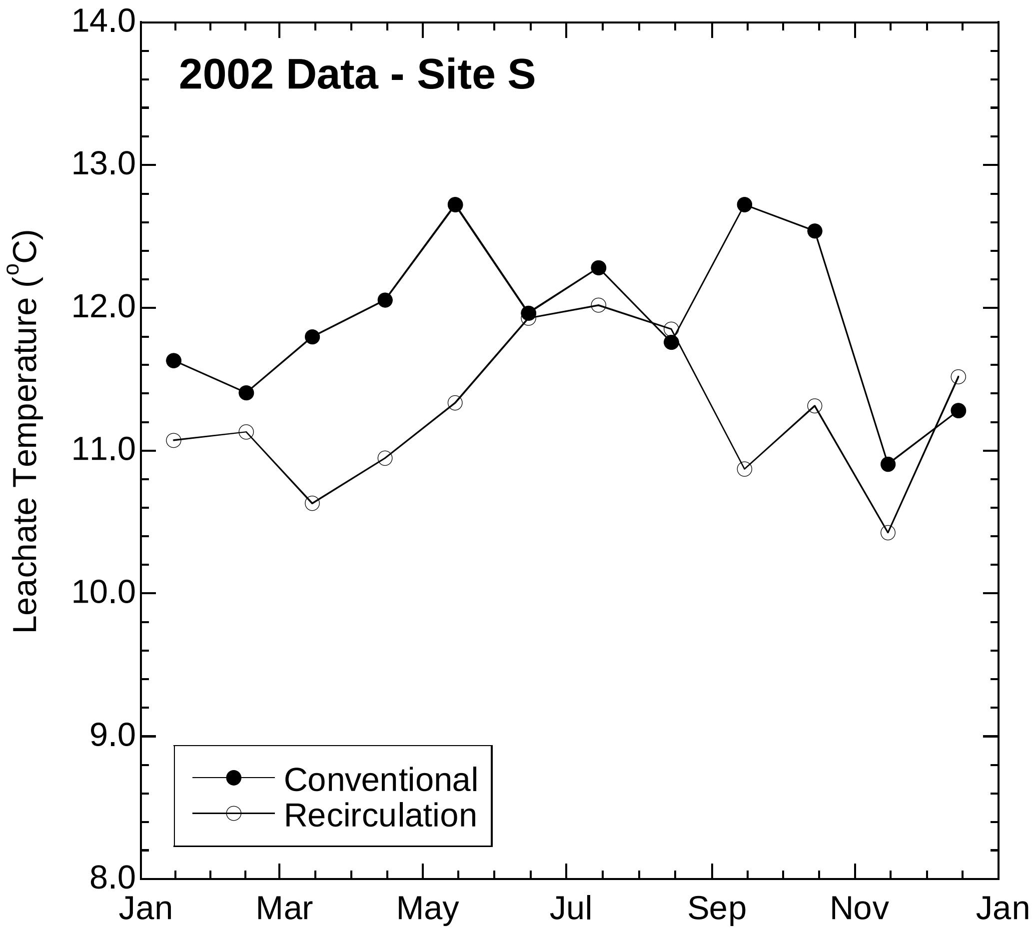


**Figure 7: Leachate temperatures measured monthly in the sumps at Site S in 2002. Temperatures are an average of the three sumps in each landfill.
Sump-to-sump variation in both landfills was less than ±1 ^{o}C. ^{o}F = 1.8 ^{o}C + 32.**

Average monthly leachate temperatures measured in the sumps of the conventional and bioreactor landfill cells at Site S during 2002 are shown in Figure 7. The temperatures were rather low and varied within a narrow range (10-13 ^{o}C) throughout the entire year. In addition, leachate temperatures in the conventional and bioreactor landfill cells were comparable, with temperatures for the conventional landfill being slightly (≈ 1 ^{o}C) higher than those for the bioreactor landfill.

Temperatures at the surface of the liner at bioreactor landfill Site Q are shown in Figure. 8. These temperatures were measured at various locations spanning the base of the landfill in both areas A and B (i.e., the areas mentioned in Sec. 5.2). Temperatures were measured at four locations in Area A (A1-A4) and three locations in Area B (B1-B3) depicting the range of temperatures across the liner system. Recirculation of leachate in this portion of Site Q began approximately 460 d after filling commenced. Thus, the data in Figure 8 provide a comparison of conditions for conventional and bioreactor operations (i.e., before and after recirculation). Low temperatures existed at the onset of monitoring because filling commenced towards the end of winter. The temperatures then gradually increased as the liner, insulated with waste, warmed up in response to heat flow from the underlying earth and the overlying waste. The gradual increase in temperature existed throughout the data record, with no apparent effect by initiation of recirculation.

Weekly average leachate head on the liner during 2002 in the conventional and bioreactor landfill cells at Site S are shown in Figure 9. Comparable leachate depths were recorded in both landfills, with those in the

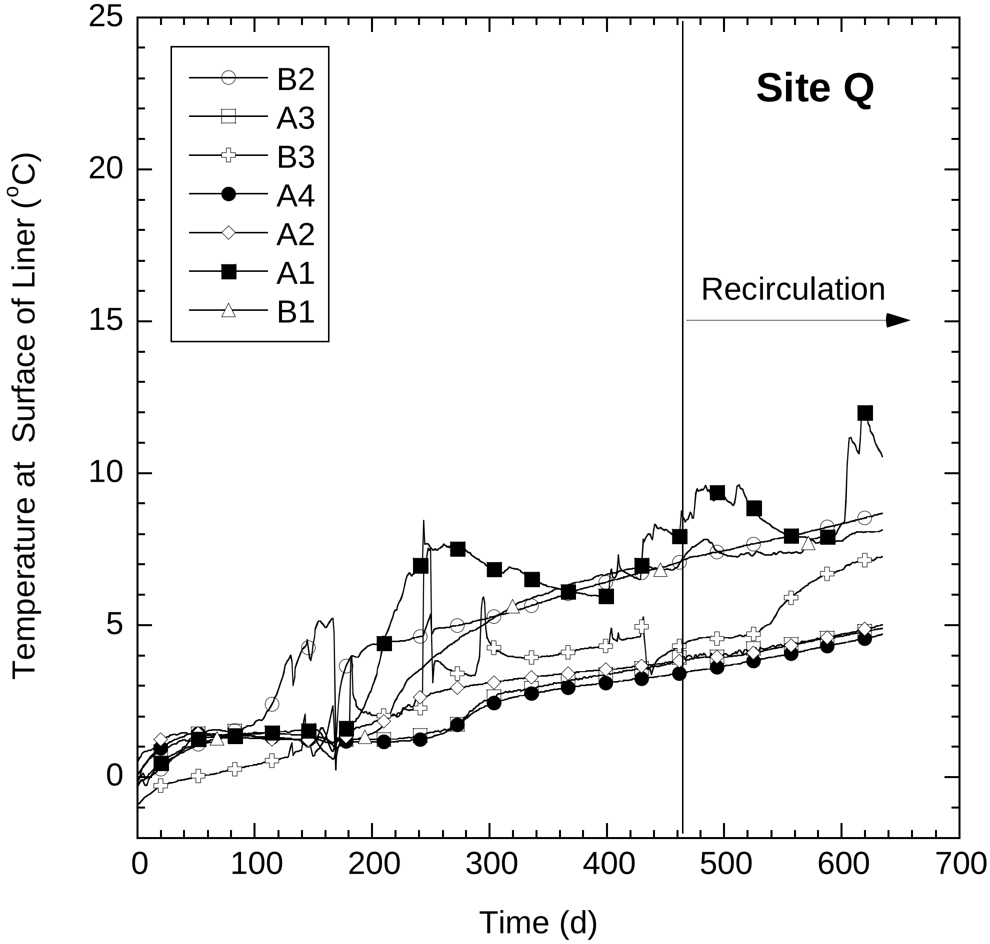


Figure 8: Temperatures measured at seven locations on the surface of the liner for Site Q. Data collection began shortly after cell began filling. Recirculation began 465 days after data collection began.°F = 1.8 °C + 32.

bioreactor landfill being slightly larger (2-3 mm, on average) than those in the conventional landfill. Leachate depths at five locations on the liner in Site Q are shown in Figure 10. These locations were in Areas B and C as described in section 5.2. There were a few points in the record before and after recirculation began when the leachate depth rose unexpectedly, with depths as large as 540 mm being recorded for a short period at one location (C3 around day 600). In general, however, the leachate head on the liner at Site Q remained very low (typically less than 50 mm), during conventional and bioreactor operations.

Leachate depths were also being recorded at Site C and Site W on a monthly basis. Head on the liner no greater than 13 mm have been recorded at Site C, regardless of whether the landfill was operating conventionally or as a bioreactor, and there was no trend in the data over time. Site W recorded a maximum leachate head of 102 mm and Sites E had recorded head on the liner values ranging between 24 and 130 mm.

5.5 Geotechnical Stability

At the time of this report, geotechnical stability problems had only occurred at Site W, which had unusually steep side slopes (1.5 H: 1 V). Only one of the stability problems was attributed to the bioreactor operation. Apparently, the high pressure of air injection (40 kPa) around the periphery of the landfill

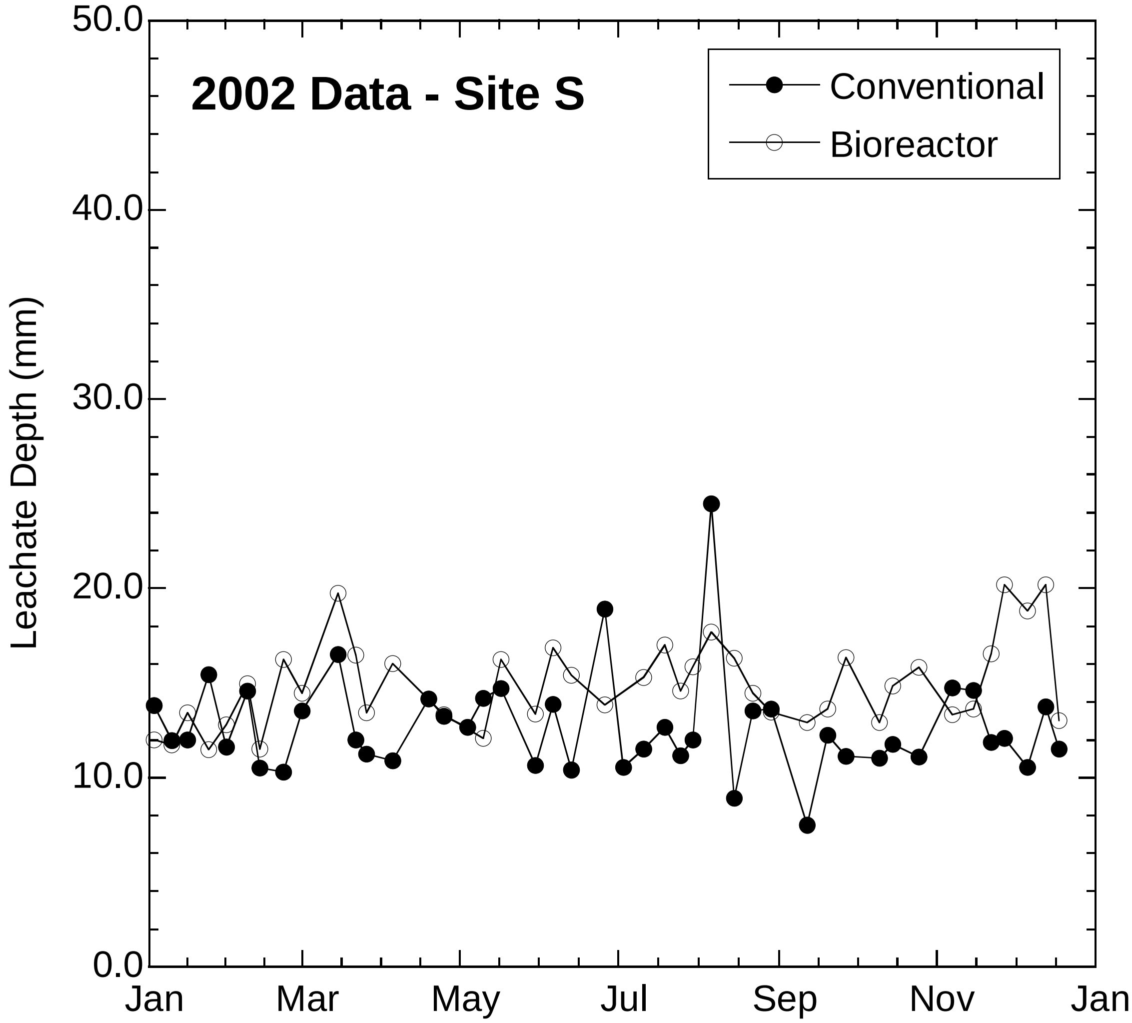


Figure 9: Weekly Average Leachate Head on the Liner in Conventional and Bioreactor Landfills Cells at Site S 1 in = 25.4 mm

forced water and leachate into the cover soils along the side slopes, causing slippage along the interface with the waste. The high water content of the cover soils was exacerbated by mulch placed on top of the cover, which increased water retention. The site owner is resolving this issue with better drainage of the cover soils.

6.0 Waste Decomposition and Stabilization

This section describes an analysis conducted to determine if bioreactor operations are stabilizing wastes by enhancing decomposition, altering leachate quality, and accelerating settlement. The analysis focused on gas production and solids analysis as indicators of decomposition rate, leachate composition as an indicator of decomposition and stabilization, and settlement as an indicator of stabilization.

6.1 Gas Production

Solid Waste decomposition to methane in anaerobic landfills is a microbially mediated process that requires the coordinated activity of several trophic groups of bacteria. A discussion of this process is provided in Appendix A. A byproduct of anaerobic decomposition is methane gas. Thus, LFG can be

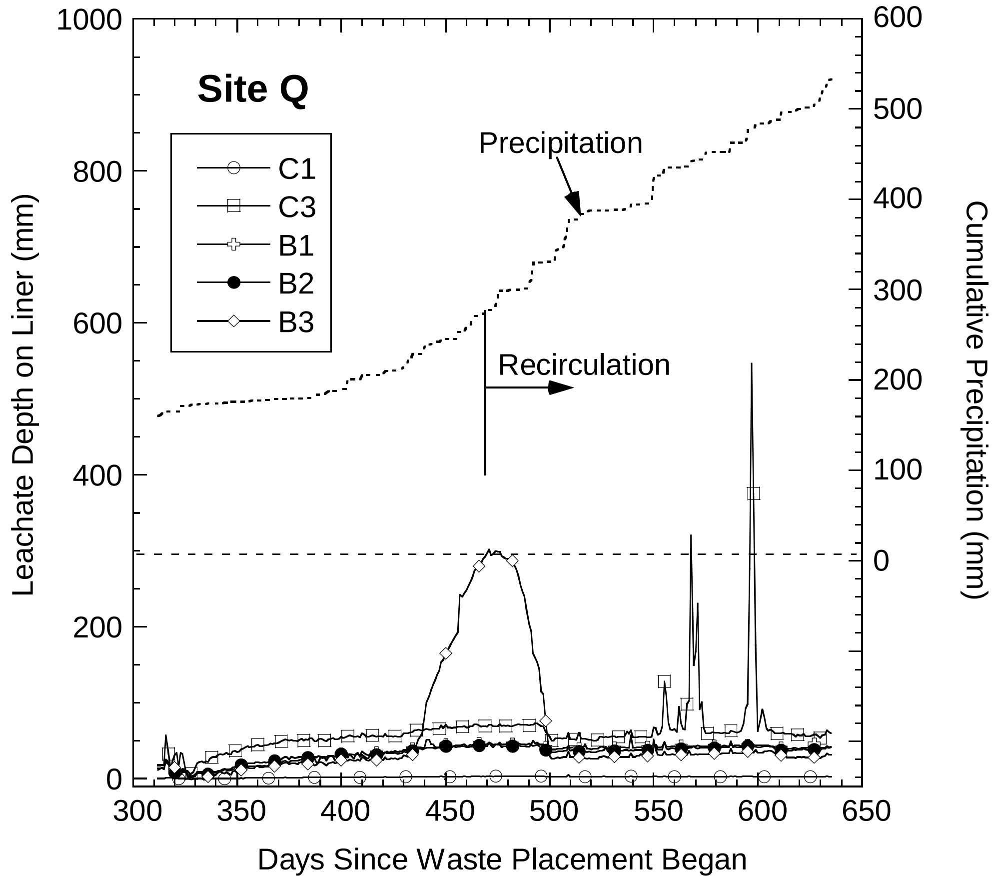


Figure 10: Leachate Head on the Liner at Five Locations at Site Q
. 1 in = 25.4 mm

analyzed to determine how landfill operations were affecting decomposition of the waste for the anaerobic sites. LFG analysis requires an evaluation of gas composition and gas production rate so that the methane production rate can be determined. Data on gas composition alone are inadequate because decomposition of cellulose and hemicellulose results in a 50-50 mix of methane and carbon dioxide. Thus, even a small amount of biodegradation of cellulose and hemicellulose will result in landfill gas that contains approximately 50% methane, regardless of the total amount of decomposition that is occurring. Similarly, gas flow rate alone is inadequate because a gas system can draw air into the waste, and dilute the methane concentration (i.e., methane production can be low even if the total gas flow rate is high).

The methane production rate (G) usually is described by the first order rate equation (USEPA 1998):

$$G = WL_o e^{-kt} \quad (1)$$

where W is the annual waste mass acceptance rate, L_o is the ultimate methane yield per wet mass of waste, and k is the decay rate. The benchmark decay rates commonly used for MSW are 0.04 yr-1 (as recommend in AP-42, USEPA 1995) and 0.05 yr-1 (as recommend in the New Source Performance Standards, USEPA 1999), both of which were developed for conventional landfills. If decomposition is occurring at a higher rate than expected for a conventional landfill (i.e., as anticipated in a bioreactor landfill), then the methane production rate predicted by Equation1 would be larger than that based on k = 0.04-0.05 yr-1. Accordingly, Equation 1 was used to determine if the gas data collected in this study indicated that bioreactor operations were resulting in enhanced decomposition rates. Sufficient data for such an analysis were available for Sites S, D, Q, and E.

6.1.1 Anaerobic Bioreactor Landfills

Methane production for Site E during 1999 to 2001 is summarized in Table 9 along with predictions made with Equation 1 using a decay rate of 0.04 yr-1. The ultimate methane yield (Lo) was set at 170 m3/Mg (assumed by site owner when making calculations), 100 m3/Mg (recommended in AP-42), or 38-54 m3/Mg. The latter two values were computed assuming 100 m3/Mg as recommended in AP-42 and considering that 46 to 62% of the waste received at the site had low methane potential (foundry sand, contaminated soil, construction and demolition debris, etc.). The numbers in parentheses in Table 9 are the ratio of measured to predicted methane production. The predicted methane production varied considerably depending on the magnitude of Lo. Regardless, the measured methane production significantly exceeded that predicted for conventional landfill operations in only one case (Lo = 38 m3/Mg). However, this comparison does not necessarily imply that bioreactor operations at Site E have elevated the rate of decomposition. For example, the efficiency of landfill gas collection was likely less than 100% because gas was not being collected from the entire site and only a small portion of final cover has been placed to date. Given the uncertainties in waste composition and the efficiency of the gas collection system, a definitive conclusion cannot be drawn regarding the effect of bioreactor operations on gas production or the decay rate at Site E.

Table 9: Measured and Predicted Methane Generation Rates for Site E. Number in Parentheses is the Ratio of Measured to Predicted Methane Production.

Year	Measured Methane Production (m^3 CH_4/yr)	Predicted Methane Production (m^3 CH_4/yr)			
		L_o = 170 (m^3/Mg)	L_o = 100 (m^3/Mg)	L_o = 54 (m^3/Mg)	L_o = 38 (m^3/Mg)
2001	$5.77x10^6$	$1.53x10^7$ (0.38)	$9.00x10^6$ (0.64)	$4.86x10^6$ (1.19)	$3.42x10^6$ (1.69)
2000	$5.70x10^6$	$1.07x10^7$ (0.53)	$6.29x10^6$ (0.91)	$3.40x10^6$ (1.68)	$2.39x10^6$ (2.38)
1999	$4.97x10^6$	$1.33x10^7$ (0.37)	$7.82x10^6$ (0.64)	$4.22x10^6$ (1.18)	$2.97x10^6$ (1.67)

Notes: 1 ft^3 = 0.028 m^3, 1 ft^3/ton = 0.031 m^3/Mg.

The control and bioreactor landfill cells at Site S permitted a unique comparison of gas production rates for conventional and bioreactor landfills operating under essentially the same conditions (except for leachate recirculation). The mean methane concentrations for the conventional and bioreactor landfills at Site S are 49% and 50%, respectively. Thus, the methane production rate per mass of waste can be compared based on the total gas production rates normalized by the mass of waste in each landfill. Gas flow rate per mass of waste is shown in Figure 11 as function of time for the conventional and bioreactor landfills. Gas flow rates from the bioreactor landfill often, but not always, were higher than those from the conventional landfill. If the gas collection systems in the control and bioreactor cells were assumed to be equally efficient, then the data in Figure 11 suggest that the bioreactor landfill was producing 14% more methane, on average, than the conventional landfill.

The assumption of equal efficiency may not be correct because vertical gas wells, as well as recirculation lines, were being used for gas collection in the bioreactor landfill, as a result the total screened length of the vertical wells in the bioreactor landfill was greater than that in the conventional landfill (i.e., the gas collection system in the bioreactor landfill may be more efficient). To evaluate the possible differences in efficiency, gas flow rates from the conventional and bioreactor landfills were compared on the basis of gas flow per unit length of well screen, as shown in Figure 12 using box plots. The average gas flow rate per unit length of well screen for the bioreactor landfill is 69% higher than that for the conventional landfill. A t-test with unequal variances was conducted to determine if the difference in gas flow rates is statistically significant. The p-statistic was determined to be 0.0003 (80 degrees of freedom), indicating that the difference in flow rates is statistically significant.

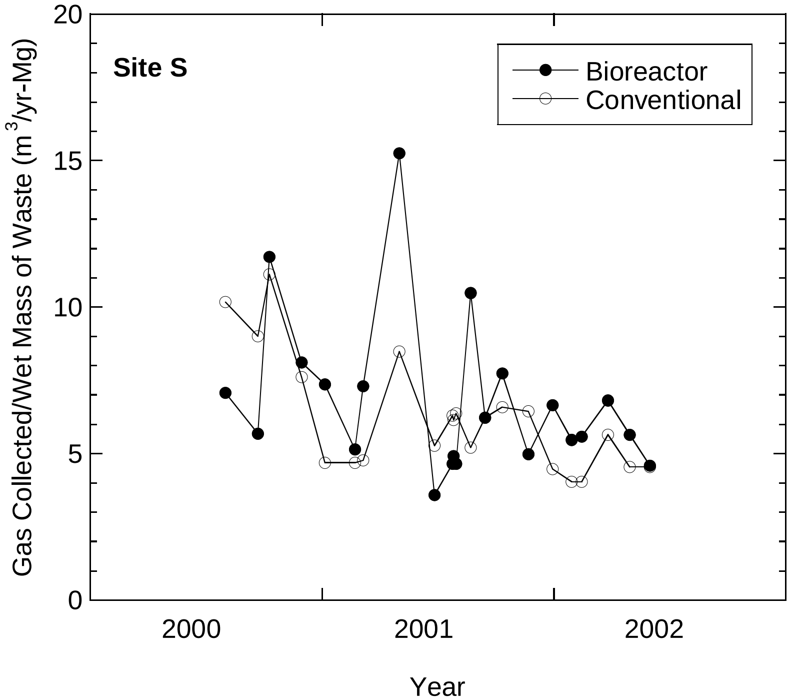


Figure 11: Gas Collected From Conventional and Bioreactor Landfills at Site S Per Unit Mass of waste
1 ft^3/ton-yr = 0.031 m^3/Mg-yr.

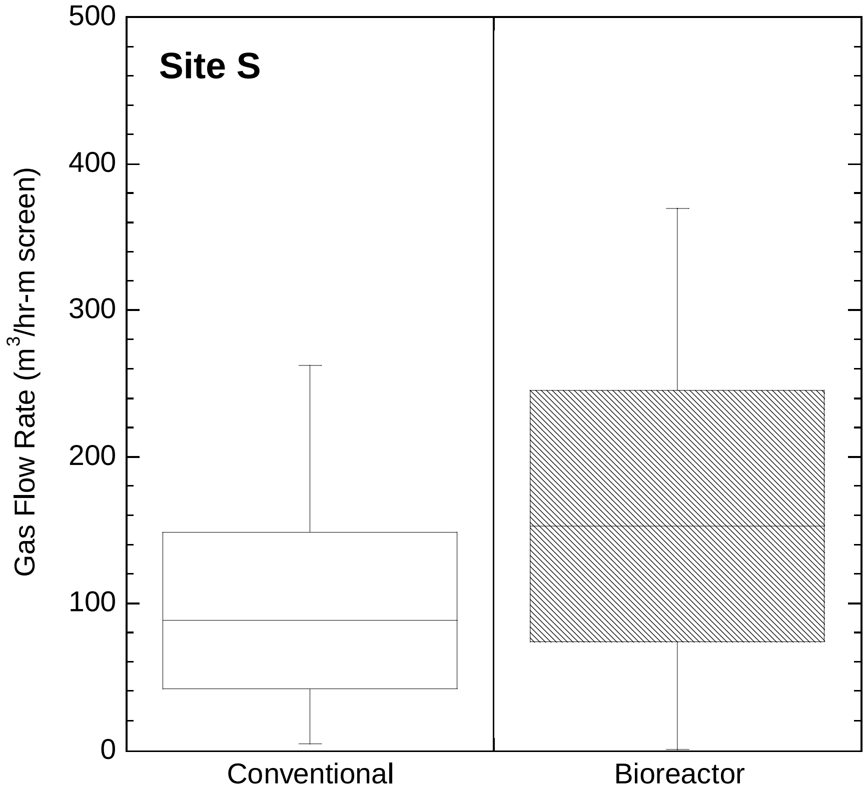


Figure 12: Box Plots Showing Gas Flow Rates Per Unit Length of Collection Well for Conventional and Bioreactor Cells at Site S.
1 scfm/ft = 5.58 m^3/hr-m

Engineers for Site S used the gas data to determine average gas productions rates of 0.0044 m3 gas/kg waste-yr for the conventional landfill and 0.0069 m3 gas/kg waste-yr for the bioreactor landfill. These gas production rates were compared to predictions made with Equation 1 assuming that the mass of waste in the bioreactor landfill was buried in equal quantities over 6 years (87,000 Mg/yr), Lo = 100 m^3 CH_4/Mg (i.e., the MSW was largely methane generating), and that the gas collection systems were completely efficient.

Calculations were made for k = 0.05 and 0.1 yr-1. For a seven-year period, these calculations yielded a gas production rate 0.00818 m3 gas/kg-yr for k = 0.05 yr-1 and 0.013 m3 gas/kg-yr for k = 0.1 yr-1, both of which were higher than the measured gas production rate. Thus, although the measured gas production is larger in the bioreactor, the data do not support k > 0.05 yr-1.

One reason the bioreactor landfill cell was producing less gas than expected was that recirculation had only been occurring for approximately 3 years at the time of the analysis. Also, the total volume of leachate recirculated at the time of analysis was relatively small, being less than that theoretically required to increase the water content of the waste by 1% (Sec. 5.3). Other potential reasons were that the gas collection system may not have been as efficient as assumed, and the fraction of the waste that is methane generating may have been less than that assumed. Regardless, the analysis does show that k is not > 0.05 yr-1.

The analysis for Site D was limited to those portions of the landfill where recirculation had been conducted for the longest period. Measured and predicted methane production rates for Site D provided by site engineers are summarized in Table 10. The predictions were made assuming Lo = 100 m3/Mg and k = 0.04 yr-1, as recommended in AP-42 for conventional landfills. The measured and predicted methane production rates were comparable for most years, except 1999. Thus, the data from Site S did not support a higher decay rate than is normally assumed for conventional landfills. This finding does not necessarily indicate that decomposition has not accelerated, but does indicate that there are insufficient data to confirm that decomposition was occurring at a rate that is higher than that generally assumed for conventional landfills.

Table 10: Predicted and Measured Methane Production Rates for Site D

Year	Predicted Methane Emission (Mg)	Measured Methane Emission (Mg)	Measured/ Predicted
1997	4,013	4123	1.03
1998	4,204	3805	0.90
1999	4,416	3380	0.77
2000	4,608	4335	0.94
2001	4,796	4322	0.90

Notes: 1 ton = 0.91 Mg.

A comparison of gas production rates for Site Q is summarized in Table 11. Site Q had operated as a bioreactor for approximately one year at the time the analysis was conducted. Gas collection began in Area A in May 2002, whereas gas collection in Areas B and C began in September 2002. Four cases labeled I-IV were considered for gas production calculations using Equation 1. In all cases, the gas was assumed to contain 46% methane, which is the average methane content measured on site. In Cases I-IV, only waste that was subject to recirculation was considered in the calculations. In Case IV, all buried waste was used in the analysis. The decay rate was varied between 0.05 and 0.15 yr-1 and the ultimate yield (Lo) was set at 50 m^3/Mg (based on the composition of the waste at the site) or 100 m^3/Mg (AP-42 recommendation). For Case IV, the decay rate was set at 0.10 yr-1 for waste subject to recirculation and 0.05 yr-1 for waste not subject to recirculation.

Predicted gas production rates two years after burial are alos summarized in Table 11. The measured gas production rate was 20 m^3/min. For Lo = 50 m3/Mg, the predicted gas production rate is 26-68% lower than the measured gas production rate. For Lo = 100 m3/Mg the gas production rate is 53 to 135% of the measured gas production rate, with the larger percentages associated with higher decay rates. Moreover, comparable gas productions rates were only obtained for measured and predicted values when k was > 0.05 yr-1, regardless of the ultimate yield that was assumed. Thus, Site Q appears to be the only anaerobic bioreactor landfill where accelerated decomposition can be considered to be occurring based on the gas production data. This is important, because Site Q is the only anaerobic site being studied that was operated in a manner intended to optimize decomposition of the waste.

Table 11: Gas production at Site Q Calculated with Equation 1 for Two Years Since Burial of Waste

Case	Decay Rate (yr^{-1})	Status of Waste	Mass Producing Methane (Mg)	Predicted Gas Production Rate (m^3/min)	
				L_o = 50 m^3/Mg	L_o = 100 m^3/Mg
I	0.05	Recirculation	657,000	5.30	10.6
II	0.10	Recirculation	657,000	9.86	19.7
III	0.15	Recirculation	657,000	13.8	27.6
IV	0.10	Recirculation	657,000	13.5	27.0
	0.05	No recirculation	443,000		

Notes: 1 ton = 0.91 Mg, 1 ft^3/ton = 0.031 m^3/Mg, 1 scfm = 0.028 m^3/min.

6.1.2 Aerated Bioreactor

Site W was the only landfill that was aerated with the intention of achieving aerobic conditions. Air was being injected continuously into a 0.8 ha section of the 2.4-ha landfill using well clusters fed by three 28-m^3/min blowers. Gas composition and pressure were monitored in a series of monitoring wells placed in the refuse. Data from February 2001 through April 2002 were available for 15 monitoring wells. Methane concentrations in the wells varied from 5-50% throughout this period, with many measurements at nearly 50% methane. The high methane concentrations suggested that portions of the refuse mass were not influenced by the air injection system. The air injection piping system had problems with air leaks through 2001, which could explain why parts of the landfill were anaerobic (i.e., the system probably was not uniformly aerating the waste).

Data collected in 2002 suggested that methane concentrations were reduced when the air injection system header pressure was above 28 kPa, but no information was available on the methane emission rate. Thus, the effect of the higher pressure on the methane emitted is unclear. Moreover, the high-volume air injection system may have diluted the methane concentrations rather than reduced methane emissions. Accordingly, no definitive conclusions can be drawn regarding the rate of waste degradation or the methane emission rate for Site W.

6.2 Solids

Decomposition of solids had only been analyzed at Sites S and W. One set of solids analyses was conducted on waste excavated from Site S from both the conventional and bioreactor landfills, as reported in Goldsmith and Baker (2000). The average volatile solids content was 54% in the conventional landfill and 31% in the bioreactor landfill, suggesting that additional decomposition had occurred in the bioreactor landfill.

Solids decomposition was characterized at Site W in a series of six sampling events conducted between February 2000 (before air injection began) and April 2002. Cellulose and lignin data were only available for one sampling event after initiation of aeration, and no biochemical methane potential (BMP) data were available on post-aeration samples. In addition, there were a number of limitations to the solids data for Site W. These limitations included (i) inadequate sampling techniques, (ii) removal of material prior to measurement of moisture content and the cellulose and lignin concentrations, (iii) small samples (3-7 kg whereas 50-150 kg samples are conventionally used, Mehta et al. 2002), and (iv) a gravimetric technique for analysis in which the organic solids that do not dissolve during hydrolysis (e.g. rubber, leather, and plastics, etc.) were counted as cellulose. Consequently, inferences regarding degradation could not be made from the data collected for Site W.

6.3 Leachate Quality

Leachate quality was examined for Sites C, E, D, S, and W. A review of data from Site Q was not practical given the short time period over which the bioreactor was operating. Sites C, D, and E provided a perspective on how leachate quality changes as a result of bioreactor operations (both sites were operated conventionally, and then as bioreactors). Site D provided a long-term (20 yr) record of leachate quality from a bioreactor landfill, Site S provided a side-by-side comparison of leachate quality in conventional and bioreactor landfills, and Site W provided a perspective on the effect of aeration on leachate quality

All of the evaluated data were based on chemical analyses conducted by the site operators. Most of the samples were collected from leachate sumps or leachate holding tanks. An important issue to consider when reviewing the data is that the leachate composition typically reflects characteristics of the refuse that is just above the leachate collection system, which often has undergone more decomposition than overlying waste. When leachate from overlying less decomposed waste reaches underlying decomposed waste, the microbial community in the underlying waste converts soluble substrates in the percolating leachate to methane and carbon dioxide (e.g., a layer of actively methanogenic or well-decomposed refuse effectively acts as an anaerobic trickling filter). However, leachate may also short circuit the more decomposed layers by flow through preferential pathways. Thus, leachate composition commonly varies over a continuum representing conditions corresponding to fresh as well as well-decomposed refuse.

6.3.1 Conventional to Bioreactor Landfills

Leachate quality data for Site C are shown in Figure 13. The trends in the data for Site C were characteristic of those observed at each of the bioreactor landfills. Leachate recirculation began at Site C in the first quarter of 1998. Before recirculation began, the leachate pH was gradually increasing (Figure 13a), and was approximately 7 at the time recirculation began. With the onset of recirculation, the pH decreased slightly to about 6.5 to 6.7, perhaps due to stimulation of the hydrolytic and fermentative bacteria in the refuse, resulting in accumulation of carboxylic acids. The depression in pH lasted for approximately one year, and subsequently the pH increased and then leveled off between 7 and 8 (a condition generally favorable for methanogenesis). A similar, but larger drop in pH was observed for Site E for approximately one year (Figure 14a). Insufficient data were available for Sites S, D, and W to determine if such drops in pH are commonplace after recirculation is initiated.

Biochemical oxygen demand (BOD) at Site C was decreasing prior to the onset of recirculation, but increased during recirculation (Figure 13b), possible as a result of the accumulation of carboxylic acids. The elevated BOD persisted for approximately two years, which was followed by a relatively steady decrease (with the exception of a few spikes in late 2000) indicating that the overall level of organics in the leachate was diminishing. Within 3 years of instituting recirculation, the BOD dropped below 200 mg/L. Similar trends were observed for the chemical oxygen demand (COD) (Figure 13b). The BOD to COD ratio, which is indicative of the fraction of the organics that are degradable, varied from 0.5 to 0.7 prior to the initiation of recirculation (Figure 13c) and decreased only slightly during the first three years of recirculation. After about three years, the BOD to COD ratio decreased appreciably to approximately 0.1. Within three years of recirculation (end of 2001), the leachate characteristics at Site C were comparable to those of well decomposed refuse, suggesting that at least the bottom layer of refuse was well decomposed.

Similar trends were observed for Site E, although the BOD and COD data responded less to recirculation at Site E than at Site C (Figure 14 b and c). The spikes in BOD and COD for Site E (Figure 14b) probably reflect intermittent effects (e.g., a large influx of moisture, a load of waste that is unusually putrescible, or short-circuiting of leachate from upper layers of refuse) that stimulate hydrolytic and fermentative bacteria relative to the acetogenic and methanogenic bacteria.

Ammonia-nitrogen concentrations increased with the onset of leachate recirculation at both Sites C and E (Figures. 13d and 14d). The increase in ammonia suggests overall stimulation of biological activity with the onset of leachate recirculation, and the concentration was in the range reported for other landfills (Kjeldsen et al. 2003). Some of the leachate at Site C was treated aerobically prior to recirculation, during which a significant portion of the ammonia was converted to nitrate. However, nitrate concentrations

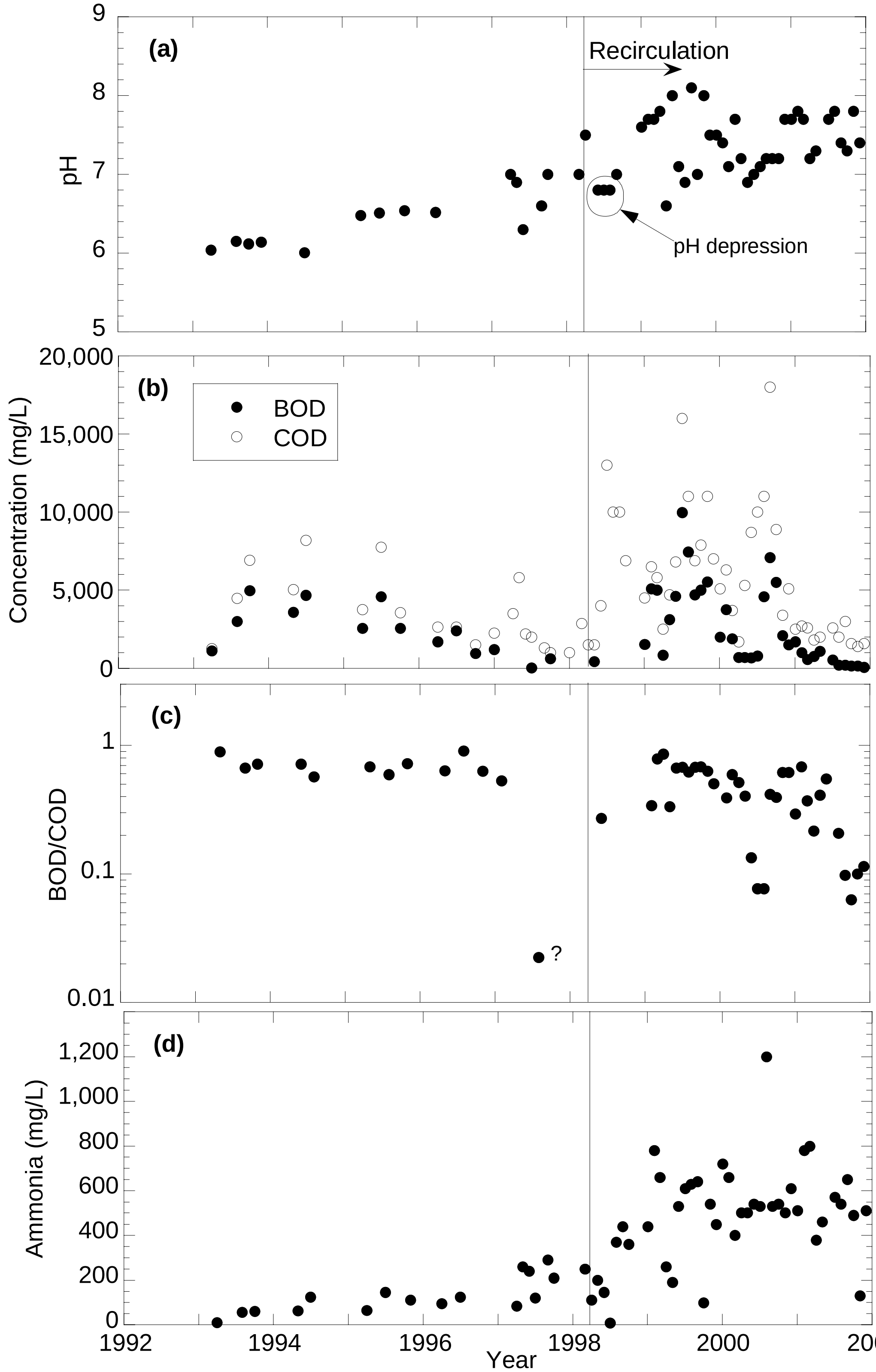


Figure 13: Leachate Quality Parameters for Site C as a Function of Time:
(a) pH, (b) BOD and COD, (c) BOD:COD Ratio, and (d) Ammonia Concentration

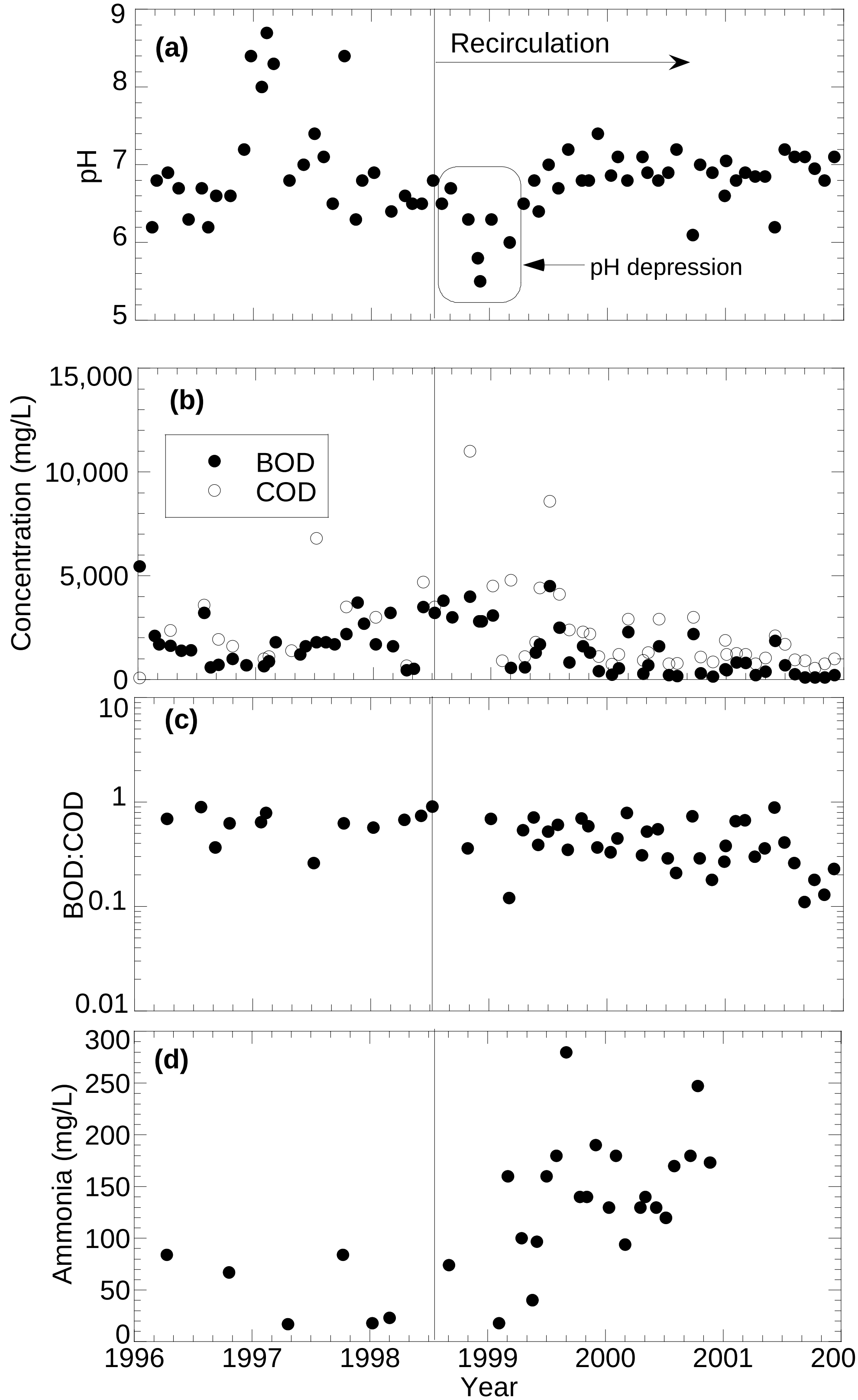


Figure 14: Leachate Quality Parameters for Site E as a Function of Time
(a) pH, (b) BOD and COD, (c) BOD:COD Ratio, and (d) Ammonia Concentration

were nearly zero in the leachate collected from Site C, which suggests that denitrification is occurring in the waste and that the bioreactor was working as a denitrification reactor. This behavior is consistent with theory and previous laboratory-scale studies (Barlaz et al. 2002b, Onay and Pohland 1998).

Leachate quality data from Area A/B at Site D are shown in Figure 15. Area A/B, which is one of the oldest bioreactors in the US, was constructed between 1980 and 1982 and was closed in 1988. The data from Site D provide an opportunity to assess whether the trends observed for other bioreactors in the program persist over the long-term. Leachate was recirculated in Area A/B between 1986 and 1995 (6 years after waste was initially buried), and leachate quality data had been collected continuously since construction. A small drop in pH may have occurred after recirculation began (i.e., as at Sites C and E), but the noise in the pH data prior to recirculation obscures the effect of recirculation on pH (Figure 15a). Near neutral pH conditions were established approximately 2-3 years after leachate recirculation began, as occurred at Sites C and E.

BOD and COD increased appreciably after recirculation began at Site D (Figure 15b). The increase in BOD and COD was followed by a relatively rapid drop after approximately 2 yr (e.g., as was observed at Site C) and then both BOD and COD asymptotically decreased to 20-100 mg/L (BOD) and 500-1000 mg/L (COD). The BODto COD ratio also began to decrease about 2-3 years after recirculation began and dropped below 0.1 after about 6 years of recirculation (Figure. 15c). The ammonia concentrations have remained elevated as was observed at Sites C and E, which is consistent with the absence of biological mechanisms for removal of ammonia under anaerobic conditions.

6.3.2 Side-by-Side Comparison of Conventional and Bioreactor Landfills

Leachate quality data are shown in Figure 16 for Site S, which provides a side-by-side comparison of conventional and bioreactor landfills. Leachate recirculation began at Site S in December 1997, but leachate quality data were only available from June 1999.

The pH climbed gradually in both landfills through 2000 (i.e., approximately 2.5 years after leachate recirculation began), after which the pH appeared to level off between approximately 7 and 8 (Figure 16a). Since 2001, the pH in both landfill cells typically has remained in a range supporting methane production. The pH data also suggest that the microbial population in the bioreactor was able to recover from the production of soluble organic matter induced by recirculation.

Leachate BOD initially was considerably higher in the bioreactor landfill cell than the conventional landfill cell. However, the BOD in the bioreactor landfill began declining approximately 2 years after recirculation was initiated (i.e., as was observed for Sites C, E, and D), and by mid 2002 (approximately 4.5 years of recirculation) the bioreactor and conventional landfills had essentially the same BOD (Figure 16b). COD showed similar trends (not shown in Figure 16). The elevated BOD in the bioreactor landfill was also consistent with the elevated production of methane in the bioreactor at Site S, as discussed in Sec. 6.1.1

The BOD to COD ratio also illustrates the relative difference in BOD between the bioreactor and conventional landfills (Figure 16c). The BOD to COD ratio was higher for the bioreactor landfill, and was still near 0.6 in mid 2002. This suggests portions of the waste were still in the acid phase, and that there was a layer of actively methanogenic refuse between the acid-phase refuse and the leachate collection system. Over time, the BOD to COD ratio of the bioreactor landfill should decrease, as was observed for Sites C, D, and E.

Ammonia concentrations in the bioreactor landfill (Figure 16d) remained relatively constant (800-1200 mg-N/L) and appreciably higher than those in the conventional landfill (< 100 mg-N/L), as was observed at Sites C, E, and D. The ammonia concentrations in the control cell are lower than those generally associated with conventional landfills (Kjeldsen et al. 2003), but insufficient data were available to explain why the ammonia concentrations are unexpectedly low.

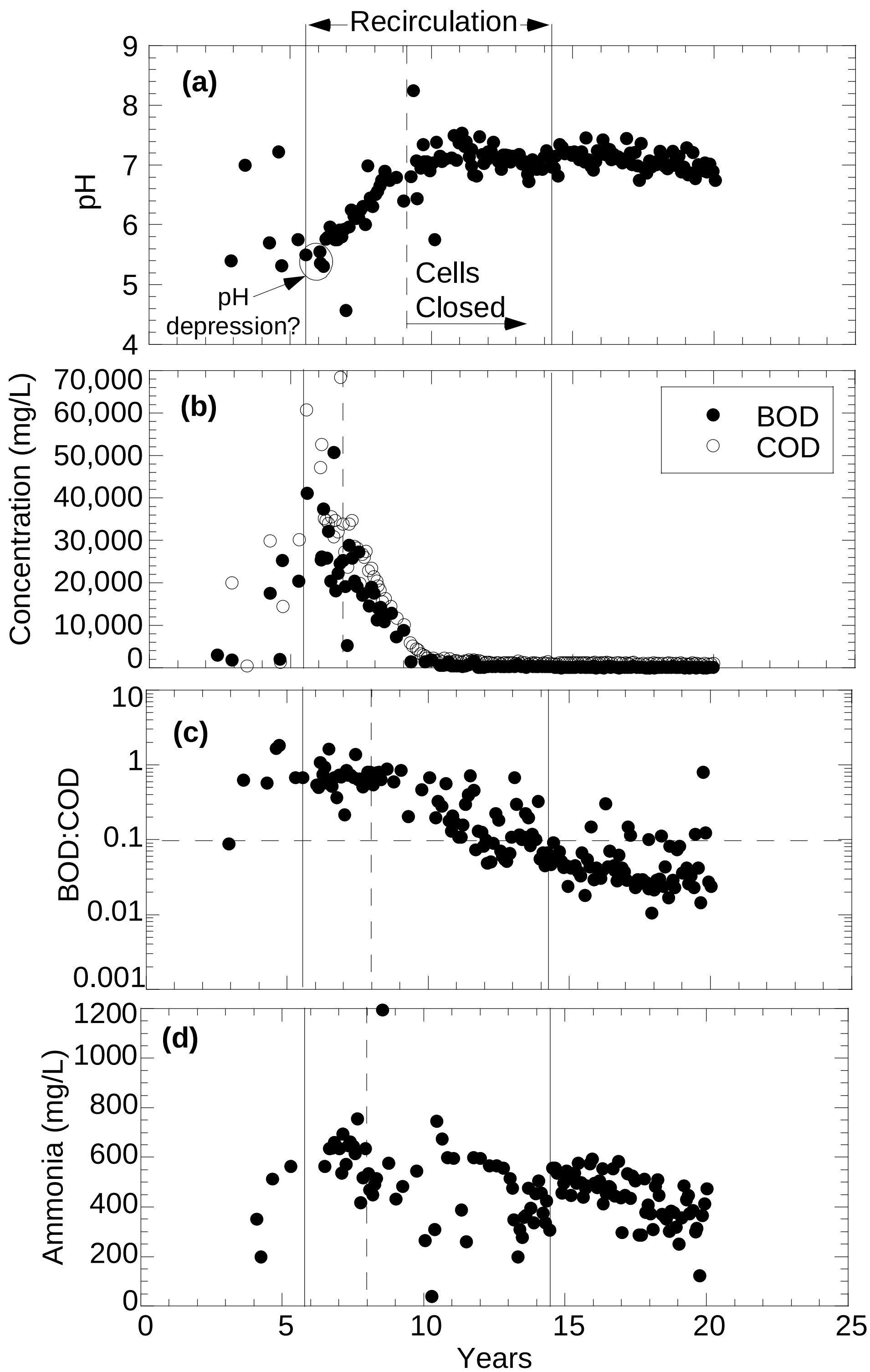


Figure 15: Leachate Quality Parameters for Site D as a Function of Time
(a) pH, (b) BOD and COD, (c) BOD:COD Ratio, and (d) Ammonia Concentration

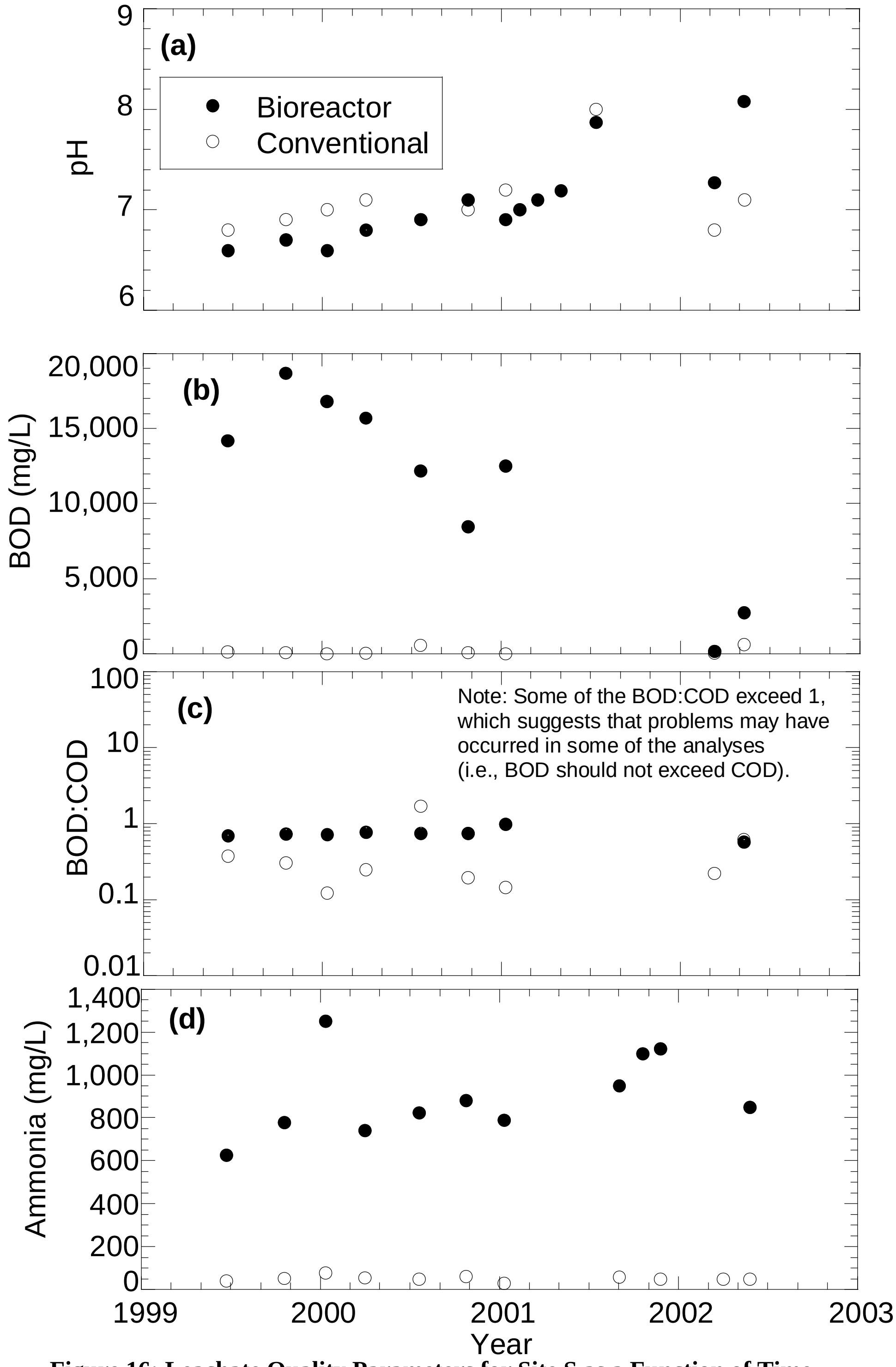


Figure 16: Leachate Quality Parameters for Site S as a Function of Time
(a) pH, (b) BOD, (c) BOD:COD Ratio, and (d) Ammonia Concentration

Concentrations of selected organic compounds in the leachate at Site S are summarized in Table 12. The concentrations are surprisingly high in the bioreactor leachate. A detailed review of organic compounds in the leachate was beyond the scope of this study. However, there is no clear reason why these elevated concentrations can be attributed to operation of a landfill as a bioreactor. An equally likely scenario is that a special waste was unknowingly buried in the bioreactor cell. Nevertheless, the broad variety of organic compounds with elevated concentrations suggests that the presence of elevated concentrations of organic compounds should be explored at other bioreactor landfills.

Table 12: Concentrations (μg/L) of Selected Organic Compounds in Leachate from the Conventional and Bioreactor Landfill Cells at Site S.

Compound			Acetone	Ethyl Ether	Methyl Ethyl Ketone	Methyl Isobutyl Ketone	Tetrahydrofuran	Diethyl phthalate	Phenol
Sampling Date	6/23/99	Conv.	374.3	259	472.4	33.9	178.2	85.2	16
		Bio.	35,560	745	46,770	1,085	2970	1770	1810
	10/19/99	Conv.	175.5	198	191.8	37.9	361.8	6.6	9.4
		Bio.	45,970	880	62,320	1745	5535	1760	2040
	1/11/00	Conv.	55.5	112.9	41.5	<8	133.5	<5	<6.7
		Bio.	53480	681	6,820	1,612	5486	1360	1720
	3/30/00	Conv.	97.7	113	94.7	<8	175.3	<5	<6.7
		Bio.	27,460	332	37,200	<320	2,600	NA	NA
	7/20/00	Conv.	619.4	324	910	56	577.6	57	21.4
		Bio.	60,350	1142	79,700	1,454	7044	1610	1520
	10/24/00	Conv.	110	83	210	13	600	< 9.0	< 10
		Bio.	26,000	380	55,000	930	6700	1500	240
	1/9/01	Conv.	<20	<2.0	<20	<3.2	23	<4.7	<4.7
		Bio.	46,000	<80	68,000	1,000	6500	1400	680

6.3.3 Effects of Aeration on Leachate Quality

Site W involved aeration of the waste, which was expected to affect the relationship between leachate quality and biodegradation. Moreover, the base of the air injection wells was 1.5 m above the leachate collection system to reduce the possibility of damaging the liner during well installation. Thus, an anaerobic layer of waste probably exists directly on top of the leachate collect system, which influences leachate quality. Given the limited amount of data and the presence of an un-aerated layer at the base of the landfill, definitive conclusions regarding the effects of aeration on leachate quality cannot be made.

Leachate quality data were only available for six sampling events, although the pH was measured regularly. The data, excluding pH, are summarized in Table 13. The pH remained relatively constant and neutral, with most pH values between 6.7 and 7.2. The BOD and COD are both relatively low, suggesting that the waste directly above the leachate collection system is well decomposed and is acting as an anaerobic trickling filter. There is no apparent trend in the ammonia concentration. However, the concentrations are typical of anaerobic waste, indicating that aeration has not facilitated complete conversion of ammonia to nitrate. This finding is consistent with the gas data (Sec. 6.1.2), which also suggest that anaerobic conditions exist in portions of the waste.

6.4 Landfill Settlement

Settlement data are being collected at Sites C, S, Q, and W. Settlement is often used as an indicator of waste decomposition and stabilization, although the processes that affect settlement of waste still remain poorly understood. Introduction of liquid into waste can cause additional settlement through a series of mechanisms, including lubrication of contacts in the waste, softening of flexible porous materials, increasing the unit weight of the waste, and biodegradation. Because many factors affect the rate and amount of settlement, inferences regarding biodegradation of waste cannot be made using settlement data alone. However, settlement data are indicative of the degree of waste stabilization. That is, larger and faster settlements caused by introduction of liquids expedite the settlement process, resulting in a waste mass that is stable in a shorter period of time.

Table 13: Leachate Quality Parameters for Site W

Parameter	Sampling Date					
	03/23/00	**08/04/00**	**11/14/00**	**07/24/00**	**12/24/01**	**07/16/02**
$CBOD_5$	18	16	690	32	61	43
Ultimate BOD	-	-	-	163	80	-
COD	160	180	1800	580	360	1500
Ammonia	19	120	250	380	140	310

Notes: Note: 1 gall = 3.78 L. Hyphen indicates quantity could not be determined $CBOD_5$ is a 5-d test, whereas ultimate BOD is a 20-d test. The site engineer indicated that 5 d may not be adequate for the seed to acclimate to the leachate, and believes that a 20 d BOD test is more appropriate. Only two 20-d BOD tests have been conducted. 1 ppm = 1 mg/L.

The data from Site S are most relevant to this study. Settlement was monitored using settlement plates placed at the surface of the waste in the conventional and bioreactor landfills after final grades were reached, permitting a direct assessment of the effect of leachate recirculation on settlement. Settlement strain (i.e., total settlement - initial thickness of waste) at each plate is shown as a function of time (i.e., since final grades were met) in Fig. 17a. Solid symbols in Fig. 17a correspond to plates in the conventional landfill, whereas open symbols correspond to the bioreactor landfill. Settlements in the bioreactor landfill have been appreciably larger than those in the conventional landfill. Over approximately 1000 d (2.7 yr), waste in the bioreactor settled 22-25%, whereas waste in the conventional cell settled less than 5%. The rate of settlement in the bioreactor has also varied with time. The average rate of settlement was approximately 14%/yr during the first 16 months, and approximately 6% during the latter 18 months of the data record. In contrast, waste in the conventional landfill settled at a relatively uniform rate of approximately 1.5%/yr.

Settlement data from Site C are shown in Fig. 17b. These data were collected after recirculation began, and thus cannot be used to drawn an inference regarding differences between conventional and bioreactor operations. Settlements at Site C are smaller than those in the bioreactor at Site S, but larger than those in the conventional landfill at Site S. The smaller settlements at Site C may reflect the smaller fraction of leachate recirculated at this site (Sec. 5). Over 2 years, the waste at Site C has settled 10 to 15%, with an average rate of settlement of approximately 7%/yr during the last 18 mos. of monitoring.

Settlement data have also been collected at Sites W, Q, and E. Settlements at Site W have been small, with a maximum settlement of 3.5% and an average settlement of 1.7% (0.8%/yr) over the 2-yr period of recirculation. Settlements at Site Q have been measured at different depths in the waste after filling, which contrast the data collected at Sites S, C, and W, which were collected during filling. Insufficient data are available for Site Q at this time to discern how recirculation has affected waste settlement. However, the total settlements at Site Q prior to recirculation ranged from 25-28% over a 2.2-yr period during which waste was placed without recirculation. Thus, the total waste settlement that may be realized through filling and recirculation may be on the order of 40-55%. Monitoring of settlement at Site E began in 2001 and is completed on an annual basis. Insufficient data are available to date to assess the settlement relative to bioreactor operations.

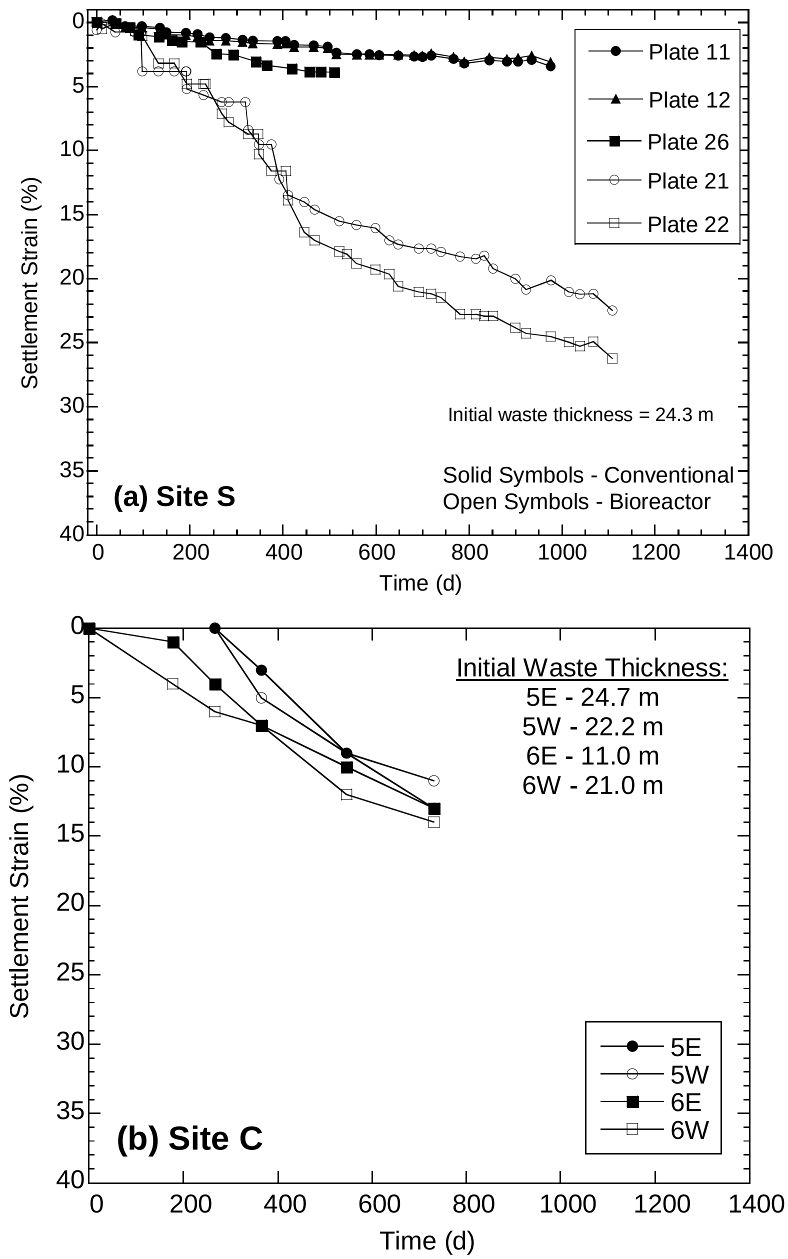


Figure 17: Settlement Strain Measured at Sites S and C using Settlement Plates
Solid Symbols are for the Conventional Landfill and Open Symbols are for the Bioreactor Landfill
1 ft = 0.305 m

7. Summary and Conclusions

This report has described a state-of-the-practice review of bioreactor landfills in North America. Six full-scale bioreactor projects were analyzed with the objective of providing a perspective of current practice and technical issues that differentiate bioreactor landfills from conventional landfills. Bioreactor landfills were defined as "landfills where waste is being degraded in a controlled fashion." This definition includes landfills that optimally control the addition of liquids to maximize the potential for degradation and stabilization of waste as well as landfills that recirculate leachate with the intention of promoting degradation and stabilization of the waste. The study consisted of site visits, review of design and documentation reports, and analysis of data provided by the sites. During the site visits, site personnel were interviewed, tours were conducted, and records evaluated.

Analysis of the operations, designs, and data suggest that bioreactor landfills operate and function in much the same way as conventional landfills, except for the recirculation of leachate and other liquids. Design modifications to permit bioreactor operations were required at only one site, and none of the landfill designs can be considered inconsistent with established standards for waste containment facilities. Although the methods used to recirculate leachate and the amounts of leachate added to the waste vary considerably, recirculation of leachate appears to have little effect on the integrity or the performance of the containment system. Leachate generation rates and leachate depths in leachate collection systems appear no different in bioreactor and conventional landfills despite the reintroduction of leachate and other liquids to the waste. Moreover, leachate and liner temperatures appear to be essentially the same in bioreactor and conventional landfills, and data from detection systems used to assess the performance of liners indicate that leakage rates and contaminants discharged from liners used for bioreactors are comparable to those for conventional landfills. In summary, there appears to be no significant difference between the functions of containment systems in conventional and bioreactor landfills.

The landfill gas data that were collected were insufficient to make a definitive assessment regarding the effectiveness of degrading waste using current bioreactor operations. Analysis of gas data indicated that biodegradation probably was accelerated at one site. This does not imply that waste is not being degraded at an accelerated rate at bioreactor landfills. For example, higher methane generation rates were found for the bioreactor at one site where conventional and bioreactor landfills are operating side by side under essentially identical conditions, which is indicative of accelerated degradation. However, ambiguities in nearly all of the gas data preclude definitive inferences regarding the effect of bioreactor operations on waste degradation and methane generation. More detailed and carefully collected data regarding methane production as well as the physical and chemical properties of the waste are needed before reliable conclusions can be drawn. However, at the site where the gas data indicate that biodegradation is accelerated, much larger volumes of liquid are being applied to the waste. Thus, the amount of liquid recirculated may need to be increased above that commonly used today if higher degradation rates are to be achieved.

Analysis of leachate quality data showed that bioreactors generally produce stronger leachate (elevated BOD, COD, and BOD:COD ratio) than conventional landfills during the first two to three years of recirculation. However, after two to three years, leachates from conventional and bioreactor landfills appear to become similar. The exception is ammonia, which tends to remain elevated in bioreactor landfills due to the absence of biological mechanisms for removing ammonia under anaerobic conditions. The duration of elevated ammonia levels is not known at this time, but should not be an issue because the leachate will be contained, minimizing the potential for release of ammonia. However, the analysis was limited to conventional wastewater parameters (BOD, COD, ammonia, pH); analyses were not conducted to evaluate whether bioreactor operations affected concentrations of metals, volatile organic compounds, or other constituents in leachate that may impact water quality.

Settlement data collected from two of the sites indicate that settlements are larger and occur much faster in landfills operated as bioreactors. Even at sites where settlements were not monitored, anecdotal reports and visual observations indicated that settlements were larger and faster once recirculation of liquids into the waste began. Thus, the waste mass in a bioreactor can be expected to settle more quickly than in a conventional landfill, which should reduce maintenance and operational problems associated with final cover systems and surface treatments applied when reusing landfills for other purposes.

An important finding of this study is that insufficient data are being collected to fully evaluate whether bioreactor methods used in practice at commercial and municipal landfills are effective in enhancing waste degradation, stabilization, and gas generation. Future studies should include more detailed monitoring and evaluation schemes that can be used to form definitive conclusions regarding the effectiveness of bioreactor operational methods. Data from such studies would also be useful in identifying more efficient and effective methods for operating bioreactor landfills.

8.0 References

Barlaz, M., Ham R., and Schaefer, D. (1990). Methane production from municipal refuse: a review of enhancement techniques and microbial dynamics. *Critical Reviews in Environmental Control*, 19(6), 557-584.

Barlaz, M., Rooker, A., Kjeldsen, P., Gabr, M., and Borden, R. (2002a). A critical evaluation of factors required to terminate the post-closure monitoring period at solid waste landfills, *Environmental Science and Technology*, 36(16), 3457 - 3464.

Barlaz, M., Price, G., and Hater, G. (2002b). Long-term nitrogen management in bioreactor landfills, *Proc. Waste Tech 2002*, Coral Springs, FL, USA, Feb. 24-7, 2002.

Benson, C. (2000). Liners and covers for waste containment, *Proc. Fourth Kansai International Geotechnical Forum, Creation of a New Geo-Environment,* Japanese Geotechnical Society, Kyoto, Japan, 1-40.

Bonaparte, R., Daniel, D., and Koerner, R. (2002). Assessment and Recommendations for Improving the Performance of Waste Containment Systems, Report No. EPA/600/R-02/099, US Environmental Protection Agency, Cincinnati, OH, USA.

Edil, T. Ranguette, V., and Wuellner, W. (1990). Settlement of municipal refuse, *Geotechnics of Waste Fills-Theory and Practice*, Special Technical Publication 1070, ASTM, West Conshohocken, PA, USA, 225-239.

El-Fadel, M., Shazabak, S., Saliby, E., and Leckie, J. (1999). Comparative assessment of settlement models for municipal solid waste landfill applications. *Waste Management and Research*, 17, 347-368.

Findikakis, A., Papelis, P., Halvadakis, C. and Leckie, J. (1988). Modelling gas production in managed sanitary landfills, *Waste Management and Research*, 6, 115.

Foose, G., Benson, C., and Edil, T. (2001). Predicting leakage through composite landfill liners, *J. of Geotechnical and Geoenvironmental Engineering,* 127(6), 510-520.

Goldsmith, C. and Baker, J. (2000). The collection and evaluation of biochemical and physical data for optimizing the operation of leachate recirculation landfills, *Proc. 23rd SWANA Annual Landfill Gas Symposium*, San Diego, CA, USA.

Hossain, M., Gabr, M., and Barlaz, M. (2003). Relationship of compressibility parameters to municipal solid waste decomposition, *J. of Geotechnical and Geoenvironmental Engineering,* 129(12), 1151-1158.

Klink, R. and Ham, R. (1982). Effects of moisture movement on methane production in solid waste samples, *Resources and Conservation*, 8, 29.

Kjeldsen, P., Barlaz, M., Rooker, A., Baun, A., Ledin, A. and Christensen, T. (2003). Present and long term composition of MSW landfill leachate – A review, *Critical Reviews in Environmental Science and Technology*, 32(4), 297-336.

Knox, K., De Rome, L., Caine, M., and Blakey, N. (1999). Observations from a review of the Brogborough Landfill 2000 test cell data." *Proc. 7th International Waste Management and Landfill Symposium,* Sardina, Italy, Environmental Sanitary Engineering Centre, Cagliari, Italy, 45-52.

Mehta, R., Barlaz, M., Yazdani, R., Augenstein, D., Bryars, M. and Sinderson, L. (2002). Refuse decomposition in the presence and absence of leachate recirculation, *J. of Environmental Engineering*, 128(3), 228-236.

Onay T. and Poland, F. (1998). In-situ nitrogen management in controlled bioreactor landfills, *Water Research*, 32(5), 1383-1392.

Pacey, J., Augenstein, D., Morck, R., Reinhart, D., and Yazdani, R. (1999). Bioreactive landfill. *MSW Management*, Sept/Oct, 53-60.

Pohland, F. (1975). Sanitary Landfill Stabilization with Leachate Recycle and Residual Treatment. Report for EPA Grant No. R-801397, USEPA National Environmental Research Center, Cincinnati, Ohio.

Pohland, F., and Kim, J. (1999). In situ anaerobic treatment of leachate in landfill bioreactors. *Water Science and Technology*, 40(8), 203-210.

Pohland, F. (1980). Leachate recycle as a landfill management option, *J. of the Environmental Engineering Division*, 106(6), 1057.

Reinhart, D., McCreanor, P., and Townsend, T. (2002). The bioreactor landfill: Its status and future, *Waste Management and Research*, 20(2), 162-171.

Reinhart, D. and Townsend, T. (1997). *Landfill Bioreactor Design and Operation,* Lewis Publishers, New York, NY.

Townsend, T., Miller, W., Lee, H., and Earle, J. (1996). Acceleration of landfill stabilization using leachate recycle. *Journal of Environmental Engineering,* 122(4), 263-268.

USEPA (1998), User''s Manual, Landfill Gas Emissions Model-Version 2.0; US Environmental Protection Agency, EPA/600/R-98/054, Washington, DC.

USEPA (1995), Compilation of Air Pollutant Emission Factors, AP-42, Fifth Ed., Vol. I: Stationary and Point Sources, US Environmental Protection Agency, EPA/600/R-98/054, Washington, DC.

USEPA (1999), Municipal Solid Waste Landfills, Volume 1: Summary of the Requirements for the New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills, EPA-453R/96-004, US Environmental Protection Agency, Office of Air Quality Planning Standards, Research Triangle Park, NC, USA.

9.0 Appendix B

Landfill Microbiology And Decomposition Of Municipal Solid Waste

By Morton A. Barlaz

The decomposition of refuse to methane in landfills is a microbially mediated process, which requires the coordinated activity of several trophic groups of bacteria. The principal substrates, which decompose to methane in landfills, are cellulose and hemicellulose. In the first part of this section the general pathway for anaerobic decomposition is reviewed. Following this general pathway review, a four-phase description of refuse decomposition is presented.

The Microbiology of Anaerobic Decomposition

Three trophic groups of anaerobic bacteria are required for the production of methane from biological polymers (cellulose, hemicellulose, and protein) as illustrated in Figure 1 (Zehnder et al. 1982). The first group of microorganisms is responsible for the hydrolysis of biological polymers. The initial products of polymer hydrolysis are soluble sugars, amino acids, long chain carboxylic acids and glycerol. Hydrolytic and fermentative microorganisms then ferment these initial products to short-chain carboxylic acids (primarily propionic and butyric acids), alcohols, carbon dioxide and hydrogen. Acetate, a direct precursor of methane is also formed. The second group of bacteria active in the conversion of biological polymers to methane is the obligate proton-reducing/fatty acid oxidizing acetogens. They oxidize the fermentation products of the first group of microorganisms to acetate, carbon dioxide, and hydrogen. The conversion of fermentation intermediates like butyrate, propionate, and ethanol is only thermodynamically favorable at very low hydrogen concentrations. Thus, these substrates are only utilized when the obligate proton-reducing acetogenic bacteria can function in syntrophic association with a hydrogen scavenger such as a methane-producing or sulfate-reducing organism. The methanogens are the third group of bacteria necessary for the production of methane. The methanogens can utilize only a limited number of substrates including acetate and hydrogen, which are the major precursors of methane in landfills. The methanogens are most active in the pH range 6.8 to 7.4 (Zehnder 1978). As a group, the methanogens control the pH of their ecosystem by the consumption of acetate and regulate the flow of electrons by the consumption of hydrogen, creating thermodynamically favorable conditions for the catabolism of alcohols and acids.

Should the activity of the fermentative organisms exceed that of the acetogens and methanogens, there will be an imbalance in the ecosystem. Carboxylic acids and hydrogen will accumulate and the pH of the system will fall, thus inhibiting methanogenesis.

Microbiology of Refuse Decomposition

A complex series of chemical and biological reactions is initiated with the burial of refuse in a landfill. During the initial aerobic phase, oxygen present in the void spaces of the freshly buried refuse is rapidly consumed, resulting in the production of CO2 and an increase in waste temperature due to the waste heat of aerobic metabolism. The aerobic phase in a landfill lasts only a few days because oxygen is not replenished once the waste is covered. During the aerobic phase, the waste moisture content is not typically at field capacity (Barlaz and Ham, 1993). Most leachate produced during this phase results from short-circuiting of precipitation through the buried refuse.

As oxygen sources are depleted, the waste becomes anaerobic, which supports fermentation reactions. In the second phase, the hydrolytic, fermentative, and acetogenic bacteria dominate, resulting in an accumulation of carboxylic acids, and a pH decrease. The highest BOD and COD concentrations in the leachate will be measured during this phase (Barlaz and Ham, 1993; Reinhart and Grosh, 1998). The BOD:COD ratio in the acid phase has been reported to be above 0.4 (Ehrig, 1988) or 0.7 (Robinson, 1995). As the pH is acidic, acid phase leachate is chemically aggressive and will increase the solubility of many metals.

The onset of the initial methanogenic phase (3) occurs when measurable quantities of methane are produced. The onset of this phase is likely associated with the pH of the refuse becoming sufficiently neutralized for at least limited growth of methanogenic bacteria. During this phase, the acids that accumulated in the acid phase are converted to methane and carbon dioxide by methanogenic bacteria and the methane production rate will increase (Barlaz et al., 1989a). Cellulose and hemicellulose decomposition also begins. COD and BOD concentrations begin to decrease and the pH increases as acids are consumed. The BOD to COD ratios will also decrease as carboxylic acids are consumed.

In the stable methanogenic phase (4), the methane production rate will reach its maximum, and will decrease thereafter as the pool of soluble substrate (carboxylic acids) decreases. In this phase, the rate of CH4 production is dependent on the rate of cellulose and hemicellulose hydrolysis. The pH continues to increase to steady-state carboxylic acid concentrations are on the order of a few mg/L. Some COD is present in the leachate but it is mostly recalcitrant compounds such as humic and fulvic acids (Barlaz and Ham, 1993, Christensen et al., 1994). The BOD:COD ratio will generally fall below 0.1 in this phase as carboxylic acids are consumed as rapidly as they are produced.

The four phases of refuse decomposition described above have been defined on the basis of both field and laboratory-scale data that have been summarized in earlier reviews (see Barlaz et al., 1990). However, environmental conditions in the landfill will have a significant impact on the rate of refuse decomposition and, subsequently, the time required for decomposition to proceed to the point where methane production decreases to zero. Studies on the effect of a number of factors on refuse decomposition have been summarized (Barlaz et al., 1990). The factor that has most consistently been shown to affect the rate of refuse decomposition is the moisture content and it is generally accepted that refuse buried in arid climates decomposes more slowly than refuse buried in regions that receive greater than 50-100 cm of annual infiltration into the waste.

References

Brock, T.D., M. T. Madigan, J. M. Martinko, and J. Parker. 1994. *Biology of Microorganisms*, 7th ed. Prentice Hall, Englewood Cliffs, N.J.

Barlaz, M. A., D. M. Schaefer, and R. K. Ham. 1989a. Bacterial population development and chemical characteristics of refuse decomposition in a simulated sanitary landfill. *Appl. Environ. Microbiol.* 55:55-65.

Barlaz, M. A., Ham, R. K. and Schaefer D.M., Mass balance analysis of decomposed refuse in laboratory scale lysimeters, *ASCE J. Environ. Eng.*, 115, 1088, 1989b.

Barlaz, M. A., Ham, R. K., and Schaefer, D. M., Methane Production from Municipal Refuse: A Review of Enhancement Techniques and Microbial Dynamics, *CRC Crit. Rev. Environ. Contr.*, 19, 6, 557, 1990.

Barlaz, M. A. and Ham R. K., Leachate and gas generation, *in Geotechnical Practice for Waste Disposal*, D. E. Daniel, ed., Chapman and Hall, London, 1993, 113.

Christensen, T.H., Kjeldsen, P., Albrechtsen, H.-J., Heron, G., Nielsen, P.H., Bjerg, P.L., and Holm, P.E., Attenuation of landfill leachate pollutants in aquifers, *Crit. Rev. Environ. Sci. Technol.*, 24, 119, 1994.

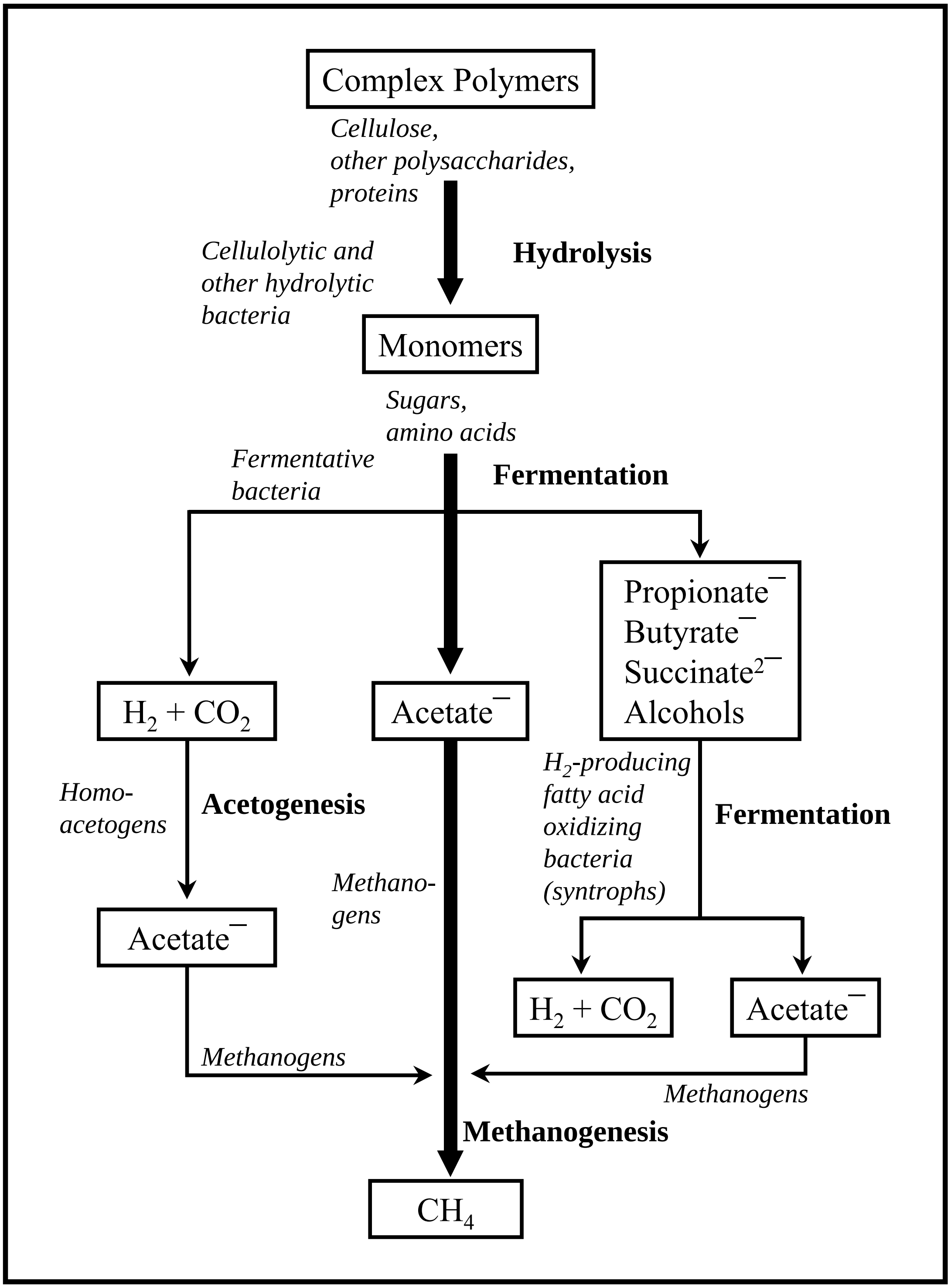
Ehrig, H.-J., Water and Element balances of landfills, in *The landfill*, Baccini, P., Ed., Springer Verlag, Berlin, Germany,1988. 83. (Lecture Notes in Earth Sciences, Vol. 20.

Reinhart, D.R., and Grosh, C.J., Analysis of Florida MSW landfill leachate quality, Florida Center for Solid and Hazardous Management, Gainesville, FL, 1998.

Robinson, H.D., The technical aspects of controlled waste management. A review of the composition of leachates from domestic wastes in landfill sites. Report for the UK Department of the Environment. Waste Science and Research, Aspinwall & Company, Ltd., London, UK, 1995.

Zehnder, A. J. B. 1978. Ecology of methane formation, p. 349-376. *In* R. Mitchell (ed.), *Water Pollution Microbiology*, vol. 2. John Wiley & Sons, Inc. New York.

Zehnder, A. J. B., Ingvorsen K., and Marti, T., Microbiology of methane bacteria, in *Anaerobic Digestion*, D. E. Hughes, D. A. et al., eds., Elsevier Biomedical Press B.V., Amsterdam, The Netherlands, 45, 1982.



FigureA.1: Overall process of anaerobic decomposition showing the manner in which various groups of fermentative anaerobes act together in the conversion of complex organic materials ultimately to methane and carbon dioxide (adapted from Brock et al. 1994).

Appendix B

Bioreactor Landfill Characterization List For Site S.
FINALIZED 1/8/04

PARAMETER OR MEASURMENT TYPE	**MEASUREMENT OR OBSERVATION**[1]	**UNITS**[2]	**MEASUREMENT METHOD**[3]	DATA SOURCE[4]	**DATA QUALITY**[5]	**COMMENTS**
I. GENERAL						
1. Site Conditions	Complete A thru E below					
A. Address (include both mailing address, such as a P.O. Box, and facility address if different	2535, 1ère Rue Sainte-Sophie (Québec) J5J 2R7 Canada					NA
B. Owner (name of county or municipal government, or private firm/owner)	INTERSAN inc.					Subsidiary of Waste Management inc.
C. Average disposal tonnage (annual or monthly)	850,000 m.t./yr 935,000 t/yr	Tonnes/yr Tons/yr	Scale	(SWANA 2002)	2	Primary data source not available.
General area of refuse collection (describe the areal extent and land usage – industrial, light industrial, residential, etc.)	Greater Montreal area Mostly residential			(Simard 2002a)	3	Verbal
2. Bioreactor Project Background	Complete A thru E below					
A. General layout	*Complete i thru viii below; attach site diagram, if available*					
i. area – total or cell	142,000. There are three cells in the bioreactor, labeled A, B, and C. Each is 10 acres	m^2	Not known	(SWANA 2002)	2	Primary data source not available.
ii. volume – total or cell	2,000,000 – for all three cells	m^3	Not known	(SWANA 2002)	2	Primary data source not available.
iii. depth – total or cell	20	m	Not known	(SWANA 2002)	2	Primary data source not available.
iv. phase	NA			NA	NA	NA

PARAMETER OR MEASURMENT TYPE	**MEASUREMENT OR OBSERVATION**[1]	**UNITS**[2]	**MEASUREMENT METHOD**[3]	DATA SOURCE[4]	**DATA QUALITY**[5]	**COMMENTS**
v. module	NA			NA	NA	NA
vi. integration w/existing site	Yes			(Simard 2002a)	1	Verified by observations during site visit.
vii. new cell or retrofit	new cell			(Simard 2002a)	1	Verified by observations during site visit.
viii. test or full-scale	full scale			(Simard 2002a)	1	Verified by observations during site visit.
B. Project funding	NA	$/yr		NA	NA	NA
C. Period of operation	2 (began in 2000)	Yrs		(SWANA 2002)	2	Primary data source not available.
– full-time vs. demonstration	full time			(SWANA 2002)	2	Primary data source not available.
D. Primary goals and objectives	*Choose i thru vi below – describe*					
i. maximize settlement and effective density	Yes			(SWANA 2002)	2	Primary data source not available.
ii. minimize leachate disposal/treatment volume	Yes			(SWANA 2002)	2	Primary data source not available.
iii. increase gas production	Yes (Potential gas purchaser)			(SWANA 2002)	2	Primary data source not available.
iv. reduce post-closure monitoring period	No			(Simard 2002a)	3	Verbal - post-closure not mandatory for this cell
v. beneficial reuse of liquids	NA			NA	NA	NA
vi. other (explain)	NA			NA	NA	NA
E. Permit approval process	Choose i thru iv below					
i. regulatory agencies (name agencies)	Quebec Ministry of Environment Certificate of authorization			(Simard 2002a)	3	Verbal
ii. regulatory exemptions (cite exemption)	None			(Simard 2002a)	3	Verbal
iii. approval conditions	None			(Simard 2002a)	3	Verbal
iv. reporting requirements	None			(Simard 2002a)	3	Verbal

II. HYDRAULIC CONTAINMENT						
1. Liner Design	Complete A thru E below					
A. Underlying geology or subbase (repeat for each layer starting with the top-most layer))	Complete i thru iii for each layer					
i. materials	Marine clay			(Simard 2002b)	2	Primary data source not available.
ii. thickness	Variable	NA	NA			
iii. characteristics	1 x 10^{-9} cm/sec. ; sensitive					
i. materials	Glacial Till					
ii. thickness	Variable					
iii. characteristics	Sandy silt with gravel					
i. materials	Bedrock			NA	NA	NA
ii. thickness	NA	NA	NA	NA	NA	NA
iii. characteristics	NA			NA	NA	NA
Additional layers – (attach another form to continue)	NA			NA	NA	NA
B. Soil barrier layer (describe each layer)	Complete i thru iii for each layer					

I. materials	The site uses a double liner system. The lower liner is a composite with a geosynthetic clay liner overlain by a 1.5 mm HDPE geomembrane. The upper line is solely a 1.5 mm geomembrane. The leak detection layer between the two geomembranes is a double layer of geonet (not a geocomposite). The upper geomembrane is protected by non-woven geotextile with M_A = 475 g/m^2 See Appendix B1			(Simard 2002b)	2	Primary data source not available.
D. Leachate Collection Layer – number	*Complete i thru iii for each layer*					
i. Materials	The LCS is crushed stone 500 mm thick. The stone gradation is between ½ to ¾ inch.			(SWANA 2002)	2	Primary data source not available.
2. Leachate Collection and Disposal	Complete A thru H below					
A. Components of leachate collection	*Describe each component in i thru v below*			(Simard 2002b)	2	Primary data source not available.
i. piping layout/spacing (attach diagram if available)	30	m				
ii. material sizes/types (porous material)	150 mm perforated HDPE Pipe. See Appendix B1	NA				
iii. sumps – number/design (describe each if different – attach diagrams if available)	3 (Base grade)	NA				

iv. pumps – number/design (describe each if different – attach diagrams if available)	3 (EPG)	NA				
v. collection areas	A) 50,285 B) 36,890 C) 47,870	m^2 m^2 m^2	Footprint design area.	(Simard 2002b)	2	Primary data source not available. See Appendix B6
B. Collection frequency	5 8	Days/ week hrs/day	Typical	(Simard 2002a)	3	Verbal - primary data source not available.
C. Volume collected	19,771	M^3	Not known	(Simard 2002b)	2	Primary data source not available.
D. Collection rate	Variable - automatic based on level control	NA	NA	(Simard 2002a)	1	Confirmed during site visit.
E. Disposal methods – sanitary, on-site treatment, recirculation, haul off-site, evaporation	Recirculation with on-site treatment			(Simard 2002a)	1	Confirmed during site visit.
G. Disposal volumes	60,006 (May 10 – Dec 20, 2002) All leachate is returned to landfill for recirculation	m^3	NA	(Simard 2002b)	2 1	Primary data unavailable Confirmed during site visit.
3. Liquids Addition						
A. Liquid sources – leachate, wastewater, surface water, sludge (type and % solids), groundwater (describe – if multiples, designate each as 1, 2, 3, etc.)	Leachate			(Simard 2002a)	1	Confirmed during site visit.
B. Methods of liquid addition – surficial	Horizontal pipe within gravel trench that are excavated into			(Simard 2002b)	2	Primary data source not available.

spraying, horizontal pipes/trenches, vertical injection wells, infiltration ponds (describe)	waste. All pipes are perforated, but have 75 ft of solid pipe on either end to prevent problems with seeps around the edges. Pipes are 300 m long or shorter, depending on filling geometry. See Appendix B3 and B3					
i. Application frequency (each source)	1	Times/day		(Simard 2002b)	2	Primary data source not available.
ii. Application rates (each source)	597	l/min		(Norstrum 2002)	2	Primary data source not available.
iii. Daily application volumes (each source)	286.5	cu.m		(Norstrum 2002)	2	Primary data source not available.
B. System components – general (describe and complete i thru viii below)	Perforated pipe within gravel filled trench. Two pipe designs are being considered. One is conventional HDPE perforated pipe The other is HYEX high capacity pipe. See Attachment B3 for conventional pipe trench detail and Attachment B4 for HYEX pipe trench detail. Details on pipes used in conventional approach are in Attachment B5.			(Simard 2002b)	2	Primary data source not available.

i. pipe sizes (list for vertical and lateral components if different)	75	mm	Design	(Simard 2002b)	2	Primary data source not available.
ii. pipe material	HDPE					
iii. perforation size	13	mm	Design			
iv. perforation frequency	100	mm	Design			
v. vertical spacing	6	m	Design			
vi. horizontal spacing	20 (Except top lift at 15 m)	m	Design			
vii. backfill material/ characteristics	Crushed stone (1/2 to ¾ in)			(Simard 2002b)	2	Primary data source not available.
viii. Other	The system is completely plumbed (no trucking or temporary lines). Liquid is pumped from sumps into a header surrounding the bioreactor cell and is distributed to recirculation trenches. Distribution to trenches is by selected by manually operated valves.			(Simard 2002b)	2	Primary data source not available.
4. Intermediate Cover Application						
A. Cover layer materials (list each as 1, 2, 3, etc.)	None			NA	NA	NA
5. Final Cover Design						
A. Description	The cover consists of a sand layer (apparently for gas)	NA	NA	(Simard 2002b)	2	Primary data source not available.

	overlain by compacted clay and top soil. The sand layer is 300 mm thick and has K = 10-3 cm/s. The clay layer is 900 mm thick and the topsoil is 200 mm thick. No information about properties of the clay layer or topsoil is provided. No surface water controls exist because filling is active.					

III GAS MANAGEMENT						
1. Air Injection						
A. Methods of air injection –	None			NA	NA	NA
2. Gas Extraction						
A. System components	Gas extraction is in horizontal trenches that are also used for leachate recirculation. Gas pipes are above the recirculation pipes. See Attachment B2 for trench layout and Attachments B3 and B4 for trench design.		Design	(Simard 2002b)	2	Primary data source not available.
i. pipe size and material	150	mm				
ii. perforation size	13	mm				
iii. perforation frequency	100	mm				
iv. vertical spacing	6	m				
v. horizontal spacing	20 (15m on top lift)	M				
vi. backfill materials	crushed stone	NA				
vii. backfill characteristics	14 to 20	Mm				
viii. automation	None	NA		NA		
B. Gas extraction frequency,	Appears to have operated only during day initially, but now operates continuously	NA	NA	(Simard 2002b)	2	Primary data source not available.
C. Efficiency of extraction system – migration, odors, collection area/influence, areal variability	No description available			NA	NA	NA

D. Post collection uses – flare, gas-to-energy, industry	Flare, plans for gas to energy			(Simard 2002a) (SWANA 2002)	2	Primary data source not available.

IV. WASTE MANAGEMENT						
1. Incoming Waste Categories and Percentages						
A. MSW breakdown	*Describe and list percentages in i thru vii*			(Norstrum 2002)	1	1) Oct. 29 to Nov 2, 2001 2) May 6 to 9, 2002
i. paper and cardboard	1) 29.3 2) 28.1	%	Estimate			NA
ii. plastics	1) 12.7 2) 12.0	%				NA
iii. metal	1) 4.9 2) 5.3	%				Ferrous metals: 4,4 % Non-ferrous metals 0,9%
iv. wood	1) 3.5 2) 10.2	%				NA
v. food waste	1) 19.0 2) 18.5	%				NA
vi. yard waste	1) 14.6 2) 7.6	%				NA
vii. other	1) 15.6 2) 16.7	%				- Other organics - Glass - Inert
B. Industrial waste (describe)	NA	%	NA	NA	NA	NA
C. Special waste (describe)	1) 0.3 2) 1.5	%	Estimate	(Norstrum 2002)	1	- Dry cell batteries - Electronics
D. Liquids (list and describe)	None	%	NA	NA	NA	NA
E. Sludges (list and describe)	None	%	NA	NA	NA	NA
2. Incoming Waste Processing						
A. C&D, transfer vs. direct disposal	None	%	NA	NA	NA	NA
B. Pre-placement processing						
i. shredding	None			NA	NA	NA
ii. mixing	None			NA	NA	NA

iii. chemical or nutrient adjustment	None			NA	NA	NA
C. Waste placement						
i. compactive effort	0.7- initial average density after compaction	m.t/cu.m	NA	NA	3	No basis provided
ii. size of active area	NA	NA	NA	NA	NA	NA
iii. lift thickness	2 – 3	m	NA	NA	1	Confirmed by on site observations
iv. moisture addition	None	NA	NA	NA	NA	NA
3. Daily Cover Application and Odor Control						
A. Methods of daily cover – tarps, soil, foam, select waste (e.g., foundry sand), spray covers	Posi-shell (30% Portland cement; remainder shredded paper and water; spray thin coating with water cannon), contaminated soil, onsite silty sand	NA	NA	(Simard 2002a) Visual observations	1	Also using fiber (2 bags = 5 40-pound bales of paper) – visual observation
i. application frequency	Applied daily, no removal	NA	NA	(Norstrom 2002)	1	Confirmed by on site observations
ii. application rates	NA	NA	NA	NA	NA	NA
iii. thickness	NA	NA	NA	NA	NA	NA
iv. removal and reuse	Not removed	NA	NA	NA	1	Visual observation
B. Other odor controls – liquid additives, gas extraction, spray covers, misting systems, neutralizing vs. masking	Gas extraction	NA	NA	Visual observation	1	Gas currently flared
4. Geotechnical Properties and Stability						
A. In-place controls – sloping, buttressing, geosynthetic reinforcement, moisture limitations	Geosynthetic slope reinforcement on below grade side slopes	NA	Design	(Simard 2002b)	2	Primary data source not available.
B. Field observations – sloughing, differential settlement, new waste vs. degraded waste behavior	None noted	NA	NA	Visual observation	1	NA

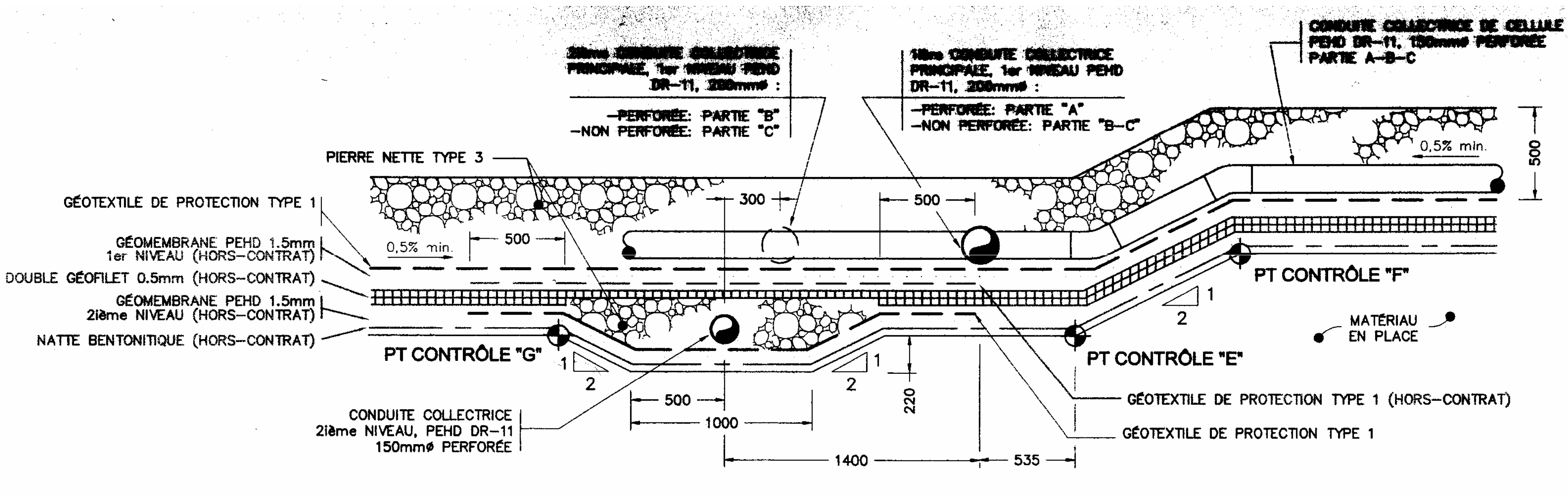
C. Seismic considerations	None	NA	NA	NA	NA	NA

V. LANDFILL/ BIOREACTOR OPERATION AND CONTROL						
1. Monitoring						
A. Waste solids	Yes	NA	NA	(Simard 2002a)	3	Results not available
i. sensors	No			NA	NA	NA
ii. frequency	NA	NA	NA	NA	NA	NA
iii. field vs. lab	NA			NA	NA	NA
iv. incoming vs. in-place	NA			NA	NA	NA
v. moisture content	NA	NA	NA	NA	NA	NA
vi. volatile solids	NA	NA	NA	NA	NA	NA
vii. cellulose fraction	NA	NA	NA	NA	NA	NA
viii. lignin fraction	NA	NA	NA	NA	NA	NA
ix. pH	NA	NA	NA	NA	NA	NA
x. BMP	NA	NA	NA	NA	NA	NA
xi. redox	NA	NA	NA	NA	NA	NA
xii. shear strength	NA	NA	NA	NA	NA	NA
xiii. compressibility	NA	NA	NA	NA	NA	NA
B. Waste mass - methods	Temperature & settlement	NA	NA	(SWANA 2002) (Norstrom 2002)	NA	NA

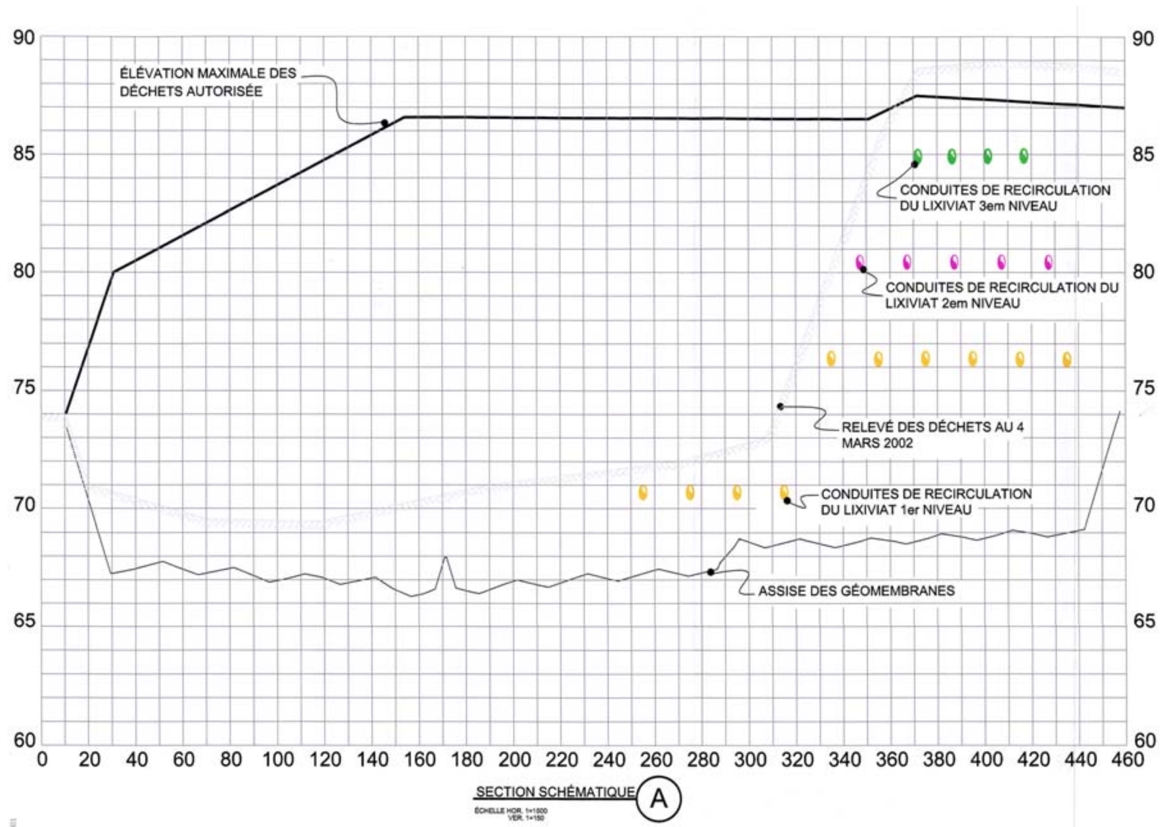
i. sensors	Thermistors for temperature. TDR being used to monitor moisture content of waste. Thermal dissipation sensors being used to monitor capillary pressure in waste.			(SWANA 2002) (Norstrom 2002)	2	Primary data source not available.
ii. frequency	Temperature – continuous Settlement – monthly	NA	NA	(SWANA 2002) (Norstrom 2002	2	Primary data source not available.
iii. temperature	Thermistors. Six thermistors each placed in Lifts 1, 2, and 3.	NA	NA	(SWANA 2002)	2	Primary data source not available.
iv. settlement	2 settlement plates per lift and per area	NA	NA	(SWANA 2002)	1	On site confirmation
v. in-place volume	Monthly surveys	NA	NA	(Simard 2002b)	2	Primary data source not available.
vi. in-place density	Monthly calculations	NA	NA			
vii. effective density	Settlement plates/monthly	NA	NA			
viii. water balance	No	NA	NA	NA	NA	NA
C. Leachate – methods	Flow rates, head, & composition	NA	NA	NA	NA	NA
i. sensors	Flow meters			(Simard 2002b)	2	Primary data source not available.
ii. frequency	1	Times/hr	NA			
iii. field vs lab	Field	NA	NA			
iv. in-place vs extracted	Measured with flow meter as leachate is pumped from sump	NA	NA			
v. temperature	Temperature is measured on liner using thermistors.	NA	NA	(SWANA 2002) (Norstrom 2002	2	Primary data source not available.
vi. head	Continuous monitoring using pressure transducers	NA	NA			
vii. composition	Yes, depends on parameters	NA	NA	(Simard 2002a)	3	No data provided

D. Liquids addition/recirculation – collection methods, frequency, field vs. lab; temperature, composition	Measured hourly. Flow meters monitoring leachate distributed to each recirculation line	NA	NA	(SWANA 2002) (Norstrom 2002	2	Primary data source not available
E. Gas – methods, sensors, frequency, field vs. lab, in-place vs. extracted; temperature, % O_2, % CH_4, % CO_2, % N_2 or balance, VOCs, NMOCs	- Weekly composition and flow at each wellhead - Daily measurement of at flare. Pitot tube used for flow rate.	NA	NA			
F. Surface emissions – methods, sensors, frequency, field vs. lab; temperature, % O_2, % CH_4, % CO_2, % N_2 or balance, VOCs, NMOCs	No	NA	NA	NA	NA	NA
G Groundwater/lysimeters – methods, sensors, frequency, field vs. lab; composition	Groundwater monitoring wells	NA	NA	(Simard 2002a)	3	Wells observed when on site; no data provided
H. Climatologic – methods, sensors, frequency, on-site vs. off-site; temperature, barometric pressure, precipitation, wind speed, wind direction	Weather station on-site; continuous measurement	NA	NA	(SWANA 2002) (Norstrom 2002	3	Weather station observed on site, but no data available for review
2. Operational Parameters or Constraints						
A. Moisture content goal or limitation	50	gal/yd^3	Not provided	(SWANA 2002)	2	Based on field capacity
B. Temperature operating range	None specified	NA	NA	NA	NA	NA
3. Closure Plan						
A. Phasing – immediate placement vs. delayed	Immediate placement	NA	NA	(Simard 2002a)	1	Part of Cell A already covered when on site
B. End-Use	None specified	NA	NA	NA	NA	NA
4. Post-Closure Maintenance						
A. Final cover maintenance – inspections, frequency, settlement problems	Site has not reached closure – no other information provided	NA	NA	(Simard 2002a)	3	No documentation of closure plan provided

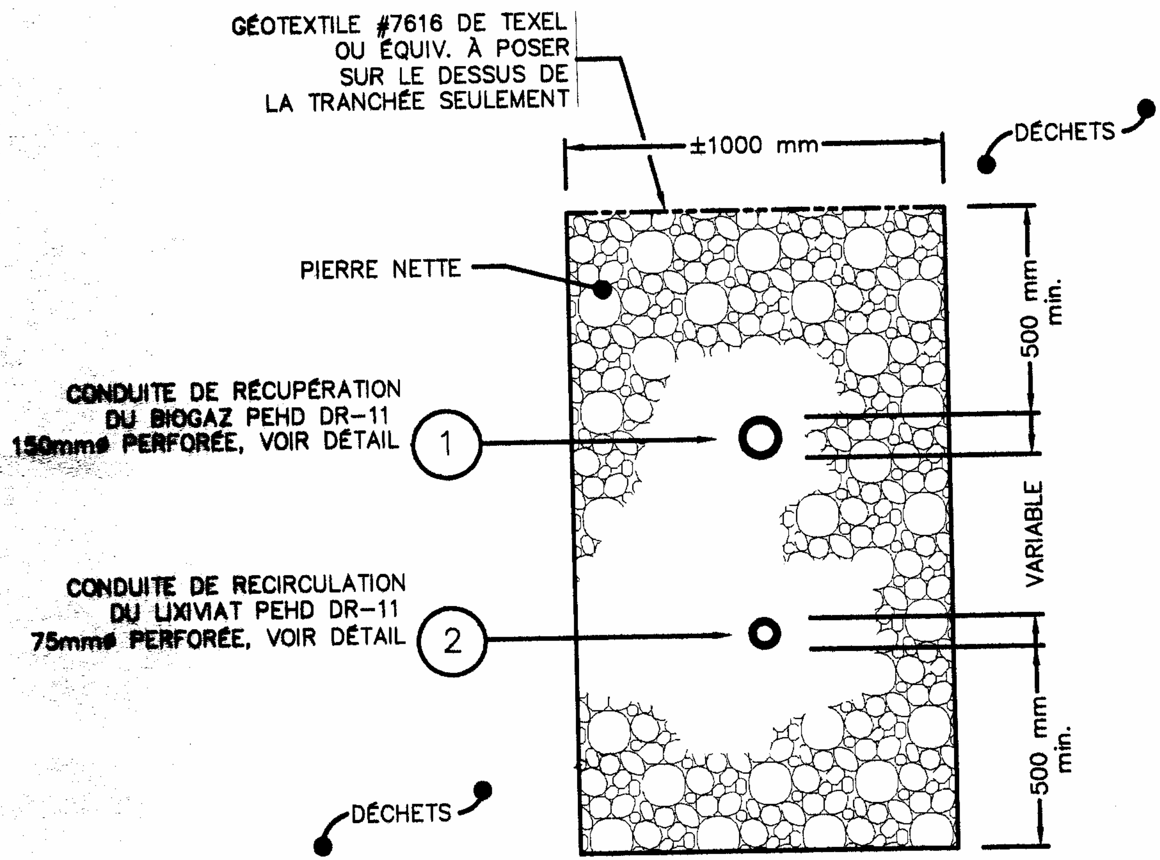
B. Environmental monitoring – groundwater, leachate, gas	Site has not reached closure – no other information provided	NA	NA	(Simard 2002a)	3	No documentation of closure plan provided
C. Leachate collection and treatment	Site has not reached closure – no other information provided	NA	NA	(Simard 2002a)	3	No documentation of closure plan provided
D. Gas extraction and use	Site has not reached closure – no other information provided, gas to energy plant being planned	NA	NA	(Simard 2002a)	3	No documentation of closure plan provided
5. Problems Encountered and Resolution						
A. Excessive Temperatures or Fire (list and describe each event; use additional paper or copy report exerpts to describe)	None noted	NA	NA	(Simard 2002a)	3	Could not be confirmed; none noted while on site
C. Liquid distribution clogging (list and describe each event; use additional paper or copy report exerpts to describe)	No	NA	NA	(Simard 2002a)	3	Could not be confirmed
C. Ponding or seeps	Seep at one trench due to faulty fitting; was repaired	NA	NA	(Simard 2002a)	3	Past experience could not be confirmed; none noted while on site
D. Leachate head > 1 ft	No	NA	NA	(Simard 2002a)	3	Could not be confirmed
E. Odors or gas migration	No	NA	NA	(Simard 2002a)	1	No excessive odors noted while on site – leachate recirculation and gas collection ongoing
F. Slope stability	No	NA	NA	(Simard 2002a)	2	No problems noted when on site
G. Cover integrity	No	NA	NA	(Simard 2002a)	2	No problems noted when on site
H. Additional costs or resources – specialized equipment, materials, or personnel	Operated by full-time person (consultant)	NA	NA	(Simard 2002a)	1	Confirmed while on site



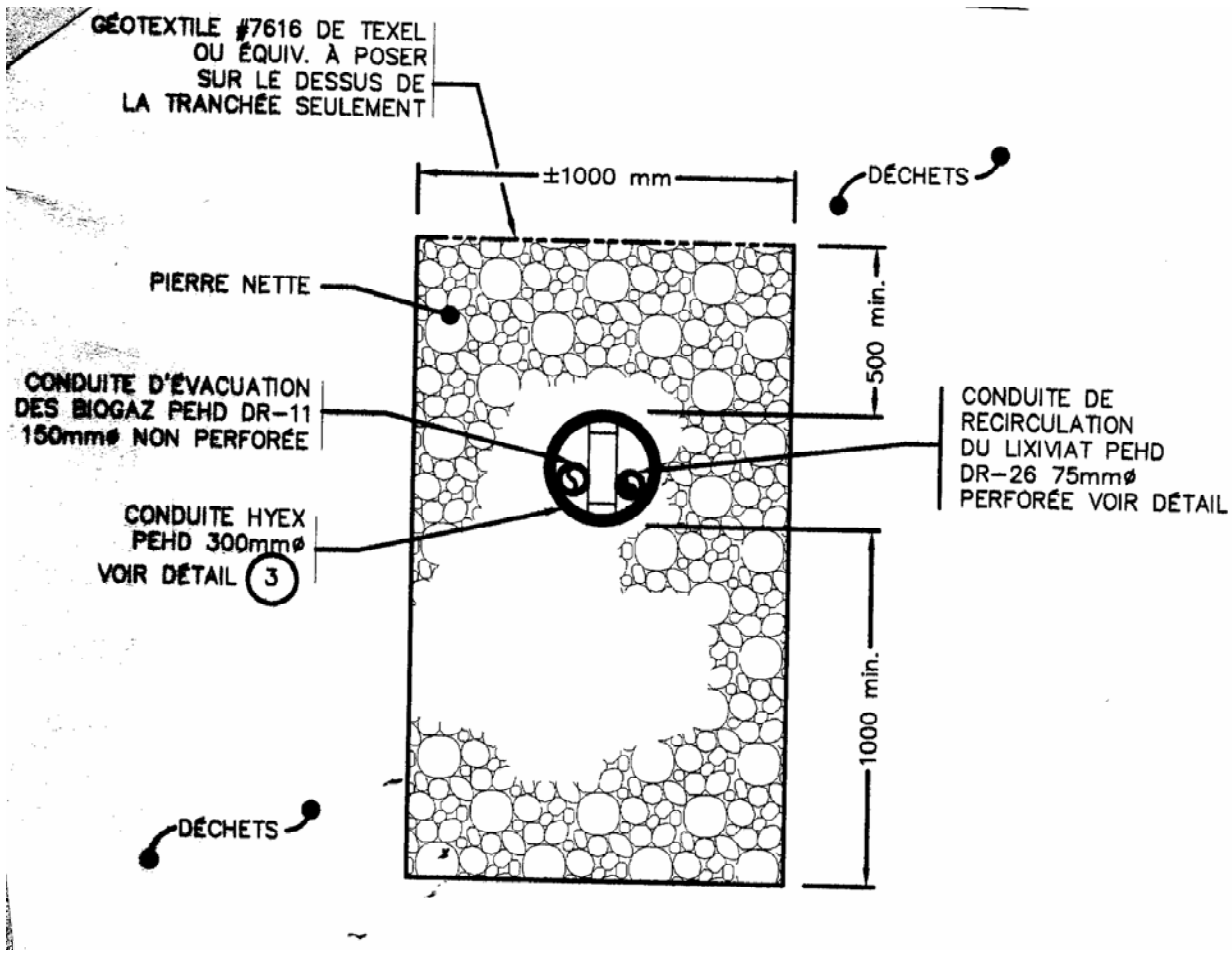
Appendix B1 – LINER AND LEACHATE COLLECTION SYSTEM



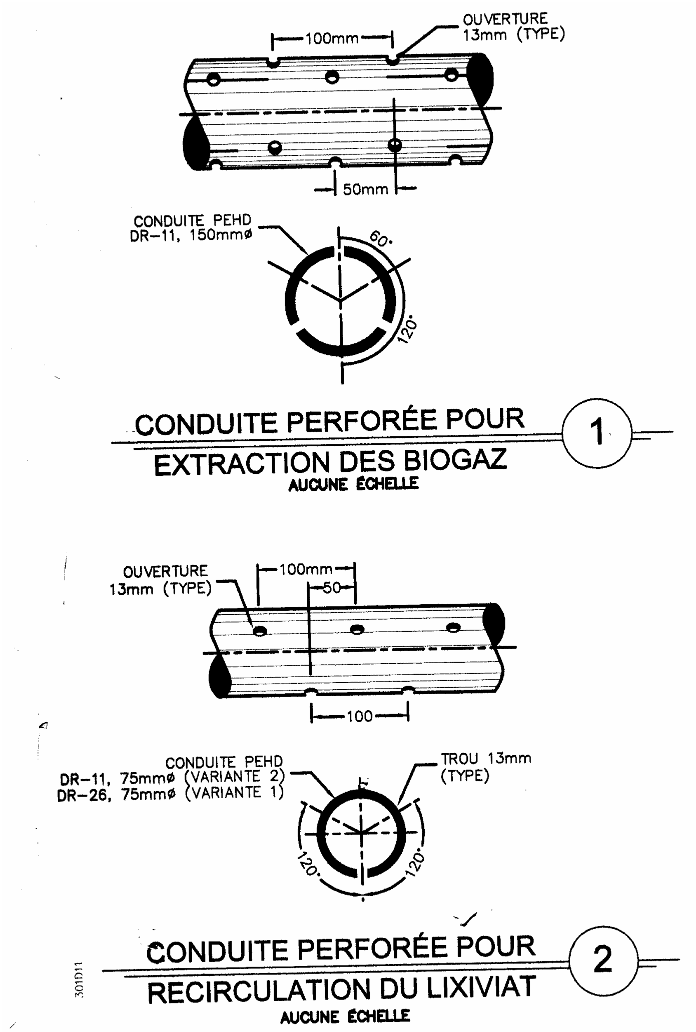
Appendix B2 – LAYOUT OF TRENCHES



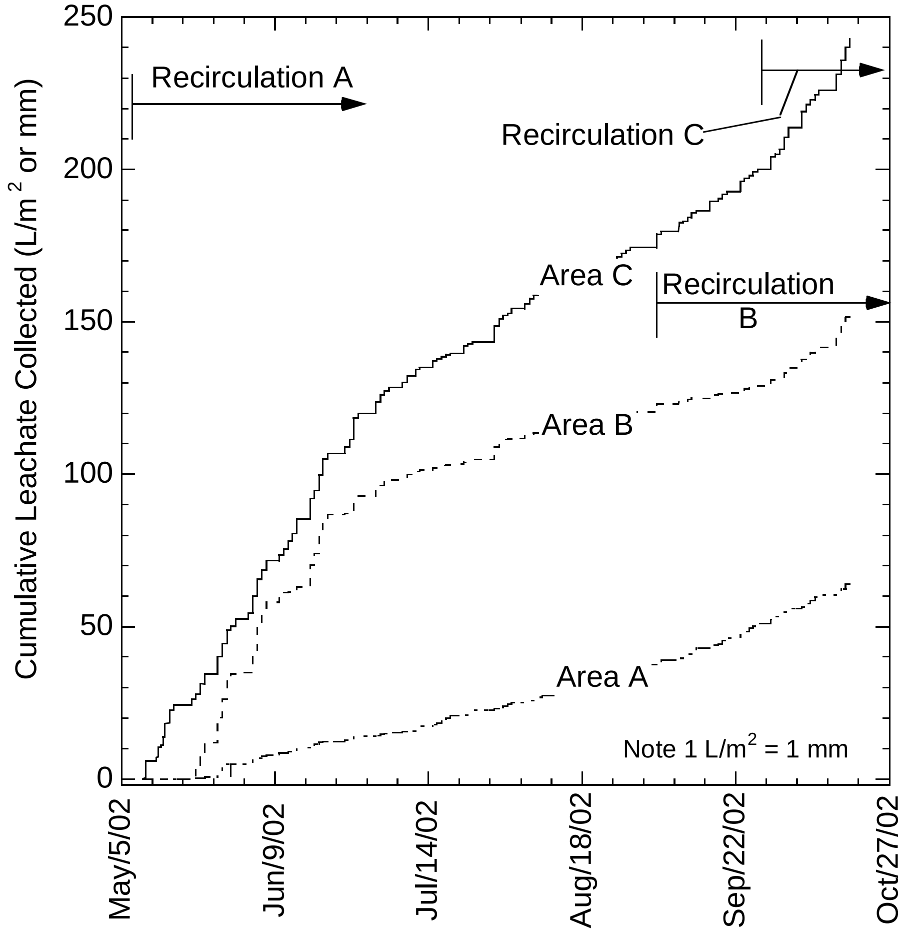
Appendix B3 – CONVENTIONAL PIPES USED FOR GAS AND LEACHATE RECIRCULATION



Appendix B4 – HYEX PIPES USED FOR GAS AND LEACHATE RECIRCULATION



Appendix B5 – PIPE DETAIL FOR CONVENTIONAL PIPES USED FOR GAS AND LEACHATE RECIRCULATION



APPENDIX B6 .CUMULATIVE LEACHATE VOLUME COLLECTED PER UNIT AREA IN AREAS A, B, AND C. VOLUMES WERE NORMALIZED BY THE FOLLOWING AREAS: A - 50,285 M^2, B – 36,890 M^2, C – 47,870 M^2.

Appendix C

Landfill Characterization List for Site W 5/21/02 – 5/23/02

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
I. GENERAL						
2. Site Conditions	Complete A thru E below					
D. Address (include both mailing address, such as a P.O. Box, and facility address if different	State Route 46 (Pinewood Road) Lieper's Fork, TN (12 miles west of Franklin, TN)					All information in this checklist, unless otherwise specifically noted, is based on a summary report prepared by Civil & Environmental Consultants, Inc. for Williamson County and this project. (CEC, 2002a)
E. Owner (name of county or municipal government, or private firm/owner)	Williamson County, TN					County government – POC is Lewis Bumpus
D. History	The overall landfill facility has been in operation since the early 1970s, accepting Class I non-hazardous solid waste materials, including domestic wastes, commercial and institutional wastes, farming wastes, tires, landscaping debris, and construction/demolition wastes. The landfill property extends over 379 acres. Since June 2000, a six-acre portion of the overall landfill site is being operated as an aerated bioreactor system.			(CEC, 2002a)		NA
E. Average disposal tonnage (annual or monthly)	2,496 (average)	Tons/mo.	Truck scale at the site	County computer	2	Original weigh tickets were not readily available

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	No longer accepting waste. The 6-acre cell being used as a bioreactor was filled from 10/95 through 1/98. The county's computer records show the following aggregate tonnage of wastes during this period: 69,880 tons ÷ 28 months 2,496 tons/month			system. A material analysis report, dated 5/21/02, was prepared for the period 10/1/95 through 1/31/98. (Williamson County, 2002)		(were reportedly in archives and would have taken several days or more to recover); therefore, data entry accuracy could not be verified. TN Dept. of Agriculture scale calibration, dated 9/28/01, was provided upon request.(TDA, 2001) The scale was certified; scale accuracy and precision could not be readily discerned from the record.
General area of refuse collection (describe the areal extent and land usage – industrial, light industrial, residential, etc.)	The County currently services approximately 125,000 residents. The major cities/towns within the Williamson County Solid Waste Planning Region served by the Williamson County solid waste collection system are Franklin, Brentwood, Nolensville, Fairview, Thompson Station, and Spring Hill.			(CEC, 2002a)	2	Upon request, county population data for 1995 through 1998 were provided. These numbers show the population range was from 101,964 in 1995 through 117,569 in 1998. (SPOT, 2002)
F. General climate	*Mean monthly temperatures ranged from 36.2 °F (January) to 79.3 °F (July), with a mean annual temperature in Nashville of 59.1 °F, based on data from 1961 to 1990. For the same period, mean monthly precipitation ranged from 2.62 inches (October) to 4.88 inches (May), with a mean annual value of 47.30 inches.*			(CEC, 2002a) (Utah, 2002)	1	General weather from (Accuweather, 2002) Appendix J data from site weather station (primary source) and local MSW station (backup). (NOAA, 2001). Texas Weather Instruments manual also provided (TWI, 2000)
2. Bioreactor Project Background	Complete A thru E below					
A. General layout	*Complete I thru viii below; attach site*					

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	diagram, if available					
i. area – total or cell	6	Acres	CEC engineering estimate from original site construction plan	(CEC, 1999a) (Caldwell & Assoc. 1992)	2	258,575.8 ft^2 or 6 acres; cell in roughly the shape of a pyramid with the top partially leveled
ii. volume – total or cell	241,991 (in-place with cover) – January 2000 235,502 (in-place with cover) – April 2002	Yd^3	CEC engineering estimate from the site construction plan and pyramid surface topography. Estimated area for 8 cross sections (based on survey data) for a volume of 241,991 yd^3 (Job 990310)	(CEC, 1999a) (Caldwell & Assoc., 1992)	2	1999 surface survey data were not provided. However, 2000 (SSS, 2000) and 2002 survey data (SSS, 2002) appear to confirm the selected surface elevations and, therefore, the calculated volume. See also drawing 200187 for surface topo. (CEC, 2002a)
iii. depth – total or cell	30 (average) 40 to 45 (maximum)	Feet Feet	Waste sampling logs	(CEC, 2002c)	2	Field notes – 2/00, 7/00, 11/00, 7/01, 12/01, and 4/02
iv. phase	NA			NA	NA	NA
v. module	NA			NA	NA	NA
vi. integration w/existing site	Non-contiguous			NA	NA	NA
vii. new cell or retrofit	Retrofit			(CEC, 2002a) (TDSWM, 2000)	1	Approval letter from TN Dept. of Solid Waste Management dated 1/6/00 (TWSWM, 2000)
viii. test or full-scale	Full-scale (for 6-acre cell) No control cell			(CEC, 2002a)	1	Personal observation
B. Project funding	Public funding - Williamson County – 100%			(CEC, 2002a) p. I-5	3	No basis or backup information provided

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
C. Period of operation	4 6/00-12/00 – anaerobic 1/01-5/02 – aerated (partially aerobic) 5/02-6/02 – system down 6/02-5/04 – remaining projected operational time	Yrs		(CEC, 2002a) p. I-5	1	Total time since start confirmed by TDSWM approval letter (TDSWM, 2000)
– full-time vs. demonstration	Full-time			(CEC, 2002a) p. I-5	2	A Williamson County official confirmed this (verbal).
D. Primary goals and objectives	*Choose i thru vi below – describe*					
i. maximize settlement and effective density	Priority 2 – also reduces steep side slope			(CEC, 2002a) p. I-6	2	No confirmation was provided, but reduction of the steep side slopes can only make closure easier
ii. minimize leachate disposal/treatment volume	Priority 1 - $0.09/gal leachate treatment plus $0.03 to $0.04/gal leachate transport			(CEC, 2002a) p. I-6	3	Leachate disposal records were not requested nor provided
iii. increase gas production	NA – no gas collection			(CEC, 2002a) p. I-6	NA	NA
iv. reduce post-closure monitoring period	Priority 3			(CEC, 2002a) p. I-6	1	A TDSWM representative confirmed (verbal) that it is willing to consider reduction of post-closure monitoring after project completion and a review of results.
v. beneficial reuse of liquids	NA			NA	NA	NA
vi. other (explain)	NA			NA	NA	NA
E. Permit approval process	Choose I thru iv below					
i. regulatory agencies (name agencies)	TN Division of Solid Waste Management (TDSWM)			(CEC, 2002a) p. I-7	1	Met agency lead – Glen Pugh

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
ii. regulatory exemptions (cite exemption)	Extended final closure until after completion of the bioreactor project			(CEC, 2002a) p. I-7	1	Confirmed with Glen Pugh of TDSWM
iii. approval conditions	TDSWM may request additional sample points, analyses, or other information			(CEC, 2002a) p. I-7	1	Confirmed with Glen Pugh of TDSWM
iv. reporting requirements	Annual reports at the TDSWM conference and as requested			(CEC, 2002a) p. I-7	2	Not confirmed

II. HYDRAULIC CONTAINMENT						
2. Hydrogeology/Subbase	Complete A thru E below					
A. Underlying hydrogeology (repeat for each layer starting with the top-most layer))	Complete I thru iii for each layer					
i. materials	Shallow soils are silty (Mountview-Baxter-Bodine)			(CEC, 2002a) (CEC, 2002d)	2	No additional information provided to substantiate this (e.g., well logs)
ii. thickness	0 to 40 (thickness)	Inches	Based on USGS classification			
iii. characteristics	Silty					
i. materials	Fine grained, cherty clay					
ii. thickness	>50 (thickness)	Feet	Based on USGS classification			
iii. characteristics	Low hydraulic conductivities and relatively high cation exchange capacity			(CEC, 2002a)	2	No additional information provided
i. materials	*Shaly limestone aquifer- residuum of the Ft. Payne Formation.*			(CEC, 2002d)	2	Groundwater Monitoring Report for May 2002 submitted to the Williamson County Solid Waste Department; not yet independently reviewed by the TDNR.
ii. thickness	*Not provided – the seasonal high level of the aquifer is approximately 60 feet (using the interpolated potentiometric surface elevation) below the bottom confining layer of the landfill.*		Liner elevations compared to potentiometric surface map			
iii characteristics	*The aquifer exhibits characteristics of both an unconfined and confined aquifer across the site.*					
2. Liner						

A. Soil barrier layer	Complete i thru iii for each layer			(CEC, 2002a) p. II-2 (TDEC, 1995) (Caldwell & Assoc., 1995)	1	TDEC approval of construction certification/drawings as described in the drainage layer detail submitted by Caldwell & Associates in 1995 and on file at CEC.
i. materials	Compacted clay					
ii. thickness	24	Inches	Construction plans plus TDEC approval			
iii. characteristics	<1x10^{-7} cm/sec saturated hydraulic conductivity					
B. Geosynthetic layer(s) – number (describe each layer)	Complete i and ii for each layer	2		NA	NA	NA
i. materials	HDPE geomembrane (smooth)			(CEC, 2002a) p. II-2 (TDEC, 1995)	1	TDEC approval of construction certification/drawings as described in the drainage layer detail submitted by Caldwell & Associates in 1995 and on file at CEC. Photographs of installation were viewed.
ii. thickness	60	Mil	Based on construction drawings			
i. materials	12 oz/yd^2 non-woven, needle-punch geotextile cushion			(CEC, 2002a) p. II-2 plus Appendix A (TDEC, 1995)	1	TDEC approval letter confirms design; original photographs of installation were viewed
ii. Thickness	See C.i. above	NA	Construction drawings	(CEC, 2002a) p. II-2 plus Appendix A (TDEC, 1995)	1	TDEC approval letter confirms design; original photographs of installation were viewed
3. Leachate Collection Layer						
A. Drainage layer(s) – number	*Complete i thru iii for each layer*	3		(CEC, 2002a) p. II-2 (TDEC, 1995)	1	TDEC approval letter confirms design.
i. materials	8 oz/yd^2 non-woven, needle-punch geotextile filter (top layer)			(CEC, 2002a) p. II-2 (TDEC,	1	TDEC approval letter confirms design.

ii. thickness	See A.i above	NA	Construction drawings	1995)		
iii. characteristics	See A.i above					
i. materials	1.5-inch crushed stone (middle layer)			(CEC, 2002a) p. II-2 plus Appendix A (TDEC, 1995)	1	TDEC approval letter confirms design; original photographs of installation were viewed (stone appeared to be angular to sub-angular)
ii. thickness	12	Inches	Construction drawings			
iii. characteristics	See comments					
B. Lysimeters – number	0	NA		NA	NA	NA
i. type	NA			NA	NA	NA
ii. other lysimeter design information (attach drawings, as appropriate)	NA			NA	NA	NA
2. Leachate Collection and Disposal	Complete A thru H below					
A. Components of leachate collection	*Describe each component in i thru v below*			NA	NA	NA
i. piping layout/spacing (attach diagram if available)	No collection pipes – only the gravel described in 1.D.	NA		NA	NA	NA
ii. material sizes/types (porous material)	NA	NA		NA	NA	NA
iii. sumps – number/design (describe each if different – attach diagrams if available)	1 Collection manhole in SE corner of cell (2% grade for complete cell to SE)			CEC, 2002a) p. II-2 (Caldwell & Assoc., 1992)	1	Construction photos viewed and presence of manhole visually confirmed
iv. pumps – number/design (describe each if different – attach diagrams if available)	1 pump in sump 1 pump each in 4 holding tanks			(CEC, 2002a) p.II-7	2	Details of pump design provided but not confirmed
v. collection areas	6 (complete bioreactor cell) 17.1 (Landfill Section 6 & 7 in SW) 33.62 ("disco" area french drain)	Acres Acres Acres	Engineering estimate based on design	(CEC, 1999b) (CEC, 2002a)	2	Based on CEC contour map GID9901
B. Collection frequency	Varies	NA	NA	NA	NA	Leachate collects in equalization basins/tanks and is totalized as pumped

						to the bioreactor
C. Volume collected	4,402,441 (leachate from 3 areas plus stormwater) 1,304,044 – LCS 1,716,678 – disco and Section 6&7 1,381,719 – stormwater	Gal/to date	Totalizing meter	(CEC, 2002b) Conversation with CEC staff	2	A water balance was performed to factor in 687,580 gal of recycle and a loss between inlet (pump totalizing meters) and outlet (equalization tank totalizing meter) of 806,839 gal due to pipe leaks, ruptures, etc.
D. Collection rate	56,698 for bioreactor area (average – rate varies with time)	Gal/mo	See C. above	See II.2.C. above	See II.2.C. above	See II.2.C. above
E. Disposal methods – sanitary, on-site treatment, recirculation, haul off-site, evaporation	100% recirculation (formerly shipped off site to MSW)			(CEC, 2002a) p. II-5 Fig. 2a Fig. 2b	1	Variable flow rate data are graphed and totalized flows shown (including down time)
F. Disposal frequency	NA	NA	NA	NA	NA	NA
G. Disposal volumes	NA	NA	NA	NA	NA	NA
H. Disposal rates	NA	NA	NA	NA	NA	NA
3. Liquids Addition						
A. Liquid sources – leachate, wastewater, surface water, sludge (type and % solids), groundwater (describe – if multiples, designate each as 1, 2, 3, etc.)	1. LCS manhole – leachate 2. Landfill disco area and Section 6&7 – leachate 3. Stormwater			See II.2.C	See II. 2.C	See II.2.C
B. Methods of liquid addition – surficial spraying, horizontal pipes/trenches, vertical injection wells, infiltration ponds (describe)	1- and 2-inch diameter vertical injection wells 1-inch wells screened starting at 3 to 5 feet below surface to the bottom of the well; direct push into refuse 2-inch wells in clusters of 3 wells, each screened for a length of approximately			(CEC, 2002a) p.II-6 Fig. 3.0 Appendix B shows specific screened elevations.	1	Additional liquid addition due to rainfall infiltration has not yet been determined. Rainfall is measured at the site and recorded in a data base. The site has attempted to measure runoff (hard to determine with mulch

	10 to 15 feet (depending on the depth at the particular location involved); new wells installed in oversize hole with crushed glass backfill.					cover). Evaporation is not known, and transpiration is expected to be insignificant due to the minimal plant cover at the site. No water balance has been completed.
i. Application frequency (each source)	Variable based on equalization tank levels	Varies	NA	NA	NA	NA
ii. Application rates (each source)	5 to 40 (variable – only source is 2,000 gal equalization tank on top of cell)	Gal/min	Unknown	(CEC, 2002a) Fig. 2a	3	Measurement method not known; specific data points not provided; no calibration data were provided for measurements
iii. Daily application volumes (each source)	NA –totalized volume (see summary for total volume for each source)	NA	NA	(CEC, 2002a) Fig. 2b	3	No calibration data provided for meter
C. System components – general (describe and complete i thru viii below)	Leachate collects in the underdrain and flows to the collection sump via gravity; it is then pumped to holding tank at the top of the cell where it is co-mingled with stormwater pumped from a nearby pond, and leachate pumped from Areas 6 & 7 (stored in 2-10,000 gallon tanks at the base of the BRLF) and the "disco" area (no intermediate storage). Leachate is pumped from the 2,000-gallon holding tank on top of the BRLF to leachate headers, and then to vertical injection wells. Total flow is metered from each of the 3 auxilliary sources (but not from direct leachate recycle) and from the 2,000-gallon holding tank.			(CEC, 2002a)	2	Generally system components were verified through visual observation, although some components were buried under ground or the thick layer of mulch on top of the cell. Also, vertical wells could not be verified because they were below grade (other than one 1-inch well that had been removed and saved.
i. pipe sizes (list for vertical and lateral components if	1 or 2 (new vertical well design which is being incrementally installed to	Inches	Observation	Visual (CEC, 2002a)	1	2-inch schedule 40 PVC out of 2,000 gal tank.

different)	replace old design) 1 (old vertical well design)	Inches				Laterals were viewed at the surface.
ii. pipe material	PVC – schedule 40			Visual (CEC, 2002a)	1	Laterals were viewed at the surface.
iii. perforation size	¼-inch wide slots in vertical wells	Inches	Ruler	Visual	1	Observed wells at the surface of the cell and measured 1 recently-removed well
iv. perforation frequency	2	Slots/inch	Ruler	Visual	1	Slots cut at site by previous contractor (not pre-slotted pipe)
v. vertical spacing	NA	NA	NA	NA	NA	NA
vi. horizontal spacing	50 (typical – spacing varies by location)	Feet	Drawing scale; visual confirmation of approximate distances	(CEC, 2002a) Fig. 3	1	Leachate injection wells are in a box shape with approximately 50-feet between wells, with 1 well centrally located. Air injection wells are in a similar grid, offset from the leachate wells. The use of both types of wells is intermittently changed, further changing the "typical" well spacing.
vii. backfill material/ characteristics	None – 1-inch wells Glass beads – newly-installed 2-inch wells (approximately a 4-inch borehole); size not known			Verbal (CEC, 2002c)	3	The bead size, characteristics, and size of the annular space on the 2-inch wells is unknown.
viii. Automation (describe; include schematics if available)	The only known automation is a float controller in the 2,000 gal tank which initiates leachate pumping when the tank reaches a pre-set level.			Verbal (CEC, 2002c)	3	The system was down and operation could not be confirmed.
4. Intermediate Cover Application						
A. Cover layer materials (list	Soil (this is the existing cover – some			(CEC, 2002a)	3	No description of soil

each as 1, 2, 3, etc.)	additional information is under final cover, which is the same in this case)					type provided
i. Cover layer thickness (list for each layer in A)	12 to 24 (an average of 30% by weight of the total cell mass)	Inches	Engineering estimates	(CEC, 2002a) p.II-12 (CEC, 2002c)	2	Confirmed by waste sample logs/field notes
ii. Cover layer characteristics (describe for each)	In-place hydraulic conductivity has been estimated at $1x10^{-7}$ to $1x10^{-8}$ cm/sec			(CEC, 2002a) p.II-13 (Geotek, 2002)	1	Soil test data were provided
B. Cover placement (describe areas)	The cover is buried beneath a layer of coarse wood mulch approximately 1 to 3 feet thick			Visual observation	2	It was difficult to tell how much soil was present; waste sampling logs confirmed 1 to 3 feet
i. vegetative growth(describe type)	Sparse cover of grass, cattails, and miscellaneous wild vegetation in sporadic areas			Visual observation	1	See project pictures.
5. Final Cover Design						
A. Gas collection or grading layer (describe and complete i thru iv)	NA			NA	NA	Information in II.5.F & G below is for intermediate cover
i. number	NA	NA		NA	NA	NA
ii. materials (describe each if multiple layers are present)	NA			NA	NA	NA
iii. thickness (for each)	NA	Inches	NA	NA	NA	NA
iv. characteristics (for each)	NA			NA	NA	NA
B. Soil barrier layer(s) - describe generally and complete i thru iv	NA	NA		NA	NA	NA
i. number	NA			NA	NA	NA
ii. materials (list each)	CCL			NA	NA	NA
iii. thickness (for each layer)	24	Inches	NA	NA	NA	NA
iv. characteristics (for each layer)	NA			NA	NA	NA

C. Geosynthetic layer(s) – describe and complete i thru iii	1992 design; not yet installed			NA	NA	NA
i. number	NA	NA		NA	NA	NA
ii. materials (for each layer)	NA			NA	NA	NA
iii. thickness (for each layer)	NA	Inches	NA	NA	NA	NA
D. Drainage layer(s) – describe and complete i thru iv	NA			NA	NA	NA
i. number	NA	NA		NA	NA	NA
ii. materials (for each layer)	NA			NA	NA	NA
iii. thickness	NA	NA	NA	NA	NA	NA
iv. characteristics	NA			NA	NA	NA
E. Rooting zone/vegetation layer(s)	NA			NA	NA	NA
i. materials	Soil			NA	NA	NA
ii. thickness	12	Inches	NA	NA	NA	NA
iii. characteristics	NA			NA	NA	NA
F. Cover placement to date – area	Intermediate soil cover placed over the cell in 1998 (see Intermediate Cover for description)	100%	Observation	(CEC, 2002a) p.II-14	2	Soil cover could be observed where mulch had been eroded or moved
i. vegetative growth – type	Minimal; mulch layer placed over bioreactor cover in spring of 2002			(CEC, 2002) p. II-14	1	Visual observation
ii. time in place	4 (soil) 2 (mulch)	years years	NA	(CEC, 2002) p. II-14	2	Actual placement times could not be verified
G. Components of surface water collection system – berms, piping/structures, basin	1. Letdown systems in SE corner and east side 2. N and NW plateau areas drain to NW corner			(CEC, 2002) p. II-14	2	General details could be observed when on site

	3. W area drains to SW corner All of these areas are covered with non-woven geotextile, except the east slope, which is covered with rip rap. Runoff is to the SW containment ponds.					

III GAS MANAGEMENT						
1. Air Injection						
A. Methods of air injection –	2-inch (and some 1-inch) vertical injection wells. Compressed air moves from 3 positive displacement blowers (a maximum of 2 run at any time) through 4- to 6-inch lateral pipes at the surface to 1-inch thermoplastic hoses at the well heads. Manual butterfly valves are used to open and close each well.			(CEC, 2002a)	1	Confirmed by visual observation
B. Horizontal pipes/trenches (describe and complete i thru iii; attach schematic if available)	NA			NA	NA	NA
i. number	NA	NA		NA	NA	NA
ii. design	NA			NA	NA	NA
iii. spacing/depth	NA	NA		NA	NA	NA
C. Vertical injection wells (describe and complete i thru iii; attach schematic if available)	Could not see the below-grade portion of vertical air injection wells to confirm design.			(CEC, 2002a); personal observation	2	One 1-inch well had been removed and kept by CEC; screen length and slot spacing were observed
i. number	Typically 2-inch diameter wells in nests screened at various depths (5 to 15-foot screen lengths) 6 wells @ 1-inch diameter 115 wells@ 2-inch diameter			(CEC, 2002a) Appendix B	2	The number of air injection wells changes with time between 41 (3/01) to 78 (6/01) to 70 (10/01); this change is due to system adjustments to control temperature and degradation.
ii. design	2-inch PVC, with two ¼-inch slots per inch			Personal observation	2	All components could not be observed and spacing could not be easily

iii. spacing	50 (on average; varies with overall design and periodic changes made to react to changing system parameters such as inadequate or excess heating	Feet	Measurement of scaled drawings			confirmed
D. System components	NA	NA	NA	NA	NA	NA
i. pipe size and material	NA	NA	NA	NA	NA	NA
ii. perforation size	NA	NA	NA	NA	NA	NA
iii. perforation frequency	NA	NA	NA	NA	NA	NA
iv. vertical spacing	NA	NA	NA	NA	NA	NA
v. horizontal spacing	NA	NA	NA	NA	NA	NA
vi. backfill materials	NA			NA	NA	NA
vii. backfill characteristics	NA			NA	NA	NA
viii. automation	NA			NA	NA	NA
E. Air application frequency	Continuous	NA	NA	(CEC, 2002e)	3	Correspondence with CEC; no additional information available.
i. air application volumes	300,000,000 to 500,000,000 (injected into the mass from Oct 2000 to Oct 30, 2002 (1,000 to 1,200 cfm – 2 blowers)	Ft^3	Estimate			
ii. air application rates	Varies with location.	NA	NA			
iii. air application strategy	Injecting compressed air into as much of the 6-acre (70,000 ton) mass as possible. The pattern of air injection and leachate injection wells varied over time, although some wells were dedicated to air or leachate injection. The configuration air injection and leachate injection was based on trial			(CEC, 2002a) Appendix B (CEC, 2002e)	2	Due to concerns that oxygen was severely limited in the bioreactor, the air application strategy has recently been modified. The bioreactor is divided vertically into 3 cells. Each cell will be

	and error and the observed response "behavior" of the bioreactor mass (temperature and gas data) to see which arrangements gave the most promising results (i.e., results that would indicate aerobic activity or dampening of CH4 and increasing temps).					aerated for an unspecified time to maximize aerobic conditions before cycling to the next cells. This strategy was selected because the operator believes the blowers are undersized.
2. Gas Extraction						
A. System components	NA – no extraction and collection system was present; only passive vent wells (liquid injection wells are interchanged with passive vent wells).	NA	NA	NA	NA	NA
i. pipe size and material	NA	NA	NA	NA	NA	NA
ii. perforation size	NA	NA	NA	NA	NA	NA
iii. perforation frequency	NA	NA	NA	NA	NA	NA
iv. vertical spacing	NA	NA	NA	NA	NA	NA
v. horizontal spacing	NA	NA	NA	NA	NA	NA
vi. backfill materials	NA	NA	NA	NA	NA	NA
vii. backfill characteristics	NA	NA	NA	NA	NA	NA
viii. automation	NA	NA	NA	NA	NA	NA
B. Air extraction frequency	Passive vent	NA	NA	NA	NA	NA
i. air extraction volumes	NA	NA	NA	NA	NA	NA
ii. air extraction rates	NA	NA	NA	NA	NA	NA
iii. air extraction strategy		NA	NA	NA	NA	NA
Efficiency of extraction system – migration, odors, collection	NA	NA	NA	NA	NA	Only minor odors were noted at the site (it was

area/influence, areal variability						not operational).
D. Post collection uses – flare, gas-to-energy, industry	NA	NA	NA	NA	NA	NA

IV. WASTE MANAGEMENT						
1. Incoming Waste Categories and Percentages						
A. MSW breakdown	*Describe and list average percentages in I thru vii*					Data from 7/00 sample event (#2); 11 samples pulled and analyzed. Mean, Std. Deviation, and Variance were calculated. All percentages are in place values
i. paper and cardboard	11	%	Bulk waste sampling methods and methods of determining percentages not specified. Percentages are after placement, not incoming. Percentages are averaged over a number of samples and total >100%.	(CEC, 2002a) p.IV-1 Fig. 6.0 shows data and statistics (note the values used (hear are averages and do not sum to 100%.	2	No further definition provided
ii. plastics	30.3	%				No further definition provided
iii. metal	4.6	%				No further definition provided
iv. wood	16.7	%				Includes yard waste
v. food waste	0	%				None noted in the waste analyses
vi. yard waste	NA – see iv	%				NA – included with wood
vii. other	29.8 – soil (cover) 10.0 – textiles 0.6 – rubber 2.2 – glass 5.3 – foam	% % % % %	SeeIV.1.A.i	(CEC, 2002a)	2	No further definition provided
B. Industrial waste (describe)	NA	%	NA	NA	NA	None reportedly accepted
C. Special waste (describe)	NA	%	NA	NA	NA	None reportedly accepted
D. Liquids (list and describe)	NA	%	NA	NA	NA	None reportedly accepted

E. Sludges (list and describe)	NA	%	NA	NA	NA	None reportedly accepted
2. Incoming Waste Processing						
A. Transfer vs. direct disposal	100 (Direct disposal from 1995 – 1998)	%	Based on historical operating information	(CEC, 2002a)	3	No original data provided to support this information.
B. Pre-placement processing						
i. shredding	NA			NA	NA	NA
ii. mixing	NA			NA	NA	NA
iii. chemical or nutrient adjustment	NA			NA	NA	NA
C. Waste placement						
i. compactive effort	Waste spread in thin layers and compacted by a bulldozer – daily and intermediate cover were liberally applied	NA	NA	(CEC, 2002a)	3	No exact thickness or compaction test data available
ii. size of active area	None – closed 1/98	NA	NA	NA	NA	NA
iii. lift thickness	NA	NA	NA	NA	NA	No information available
iv. moisture addition	NA	NA	NA	NA	NA	No information available
3. Daily Cover Application and Odor Control						
A. Methods of daily cover – tarps, soil, foam, select waste (e.g., foundry sand), spray covers	Soils – reportedly varies from 2 to 3 feet in thickness in response to NOVs received from TDSWM (thickness varies – see section on intermediate cover)	feet	Estimates	(CEC, 2002a)	3	Verbal descriptions by the consultant based on excavations done at the site. Also confirmed by the county's site manager
i. application frequency	Daily and intermediate cover	NA	See A. above	NA	NA	Data not available
ii. application rates	NA	NA	NA	NA	NA	Data not available
iii. thickness	See 3.A. above	NA	NA	NA	NA	NA

iv. removal and reuse	NA	NA	NA	NA	NA	Data not available
B. Other odor controls – liquid additives, gas extraction, spray covers, misting systems, neutralizing vs. masking	NA	NA	NA	NA	NA	Data not available
4. Geotechnical Properties and Stability						
A. In-place controls – sloping, buttressing, geosynthetic reinforcement, moisture limitations	No original structural controls were installed for slope stability. Sideslope riser pipes were installed prior to the start-up of the bioreactor as slope inclinometer monitoring units. These four pipe units are located along the south and east sideslopes, the steepest cell slopes (1.5:1 horizontal-to-vertical). The slope risers are "L-shaped" units constructed of PVC pipe and consist of a horizontal leg installed directly on top of the liner geomembrane and a vertical section that protrudes out of the sideslope for access by field personnel. The top of the vertical riser section was originally surveyed for top-of-casing elevation. In addition, the horizontal coordinates (x,y) were surveyed. These x,y,z coordinates provide a baseline for monthly monitoring of potential slope movement. Additionally, moisture injection at the very top perimeter of the south and east slopes, immediately above the top of each slope, was suspended after minor veneer slope failures occurred on both slopes on May 4, 2002 (see section IV 3b below). A buttress, consisting of a			(CEC, 2002a) p. IV-3, Figure 7.0, & App. C	1	Visual confirmation

	sand underdrain layer and rock overlay portion, was constructed along the south slope to prevent further slope displacement and dissipate pore pressures along the slope.					
B. Field observations – sloughing, differential settlement, new waste vs. degraded waste behavior	2 veneer failures It appears that these failures were due to a combination of the steep side slopes, moisture addition too close to the side wall, and heavy local rainfall in the spring of 2002. Leachate addition has been stopped close to the sidewalls to reduce the chances of additional veneer failures.	NA	Visual observation	(CEC, 2002a) p. IV-4 App. H	1	The steep side slopes have failed in several places on the SE and E sides of the cell. Stone has been moved into place in these areas to prevent further failures, although no preventive measures (other than control of leachate addition) are in place on other side walls.
C. Seismic considerations	No studies conducted	NA	NA	(CEC, 2002a) p. IV-6	NA	NA

V. LANDFILL/ BIOREACTOR OPERATION AND CONTROL						
1. Monitoring						
A. Waste solids	Waste samples were collected by stratified random samples from 3 primary horizontal zones. Samples were collected from the flights of hollow stem augers at 10 – 13 drill locations. Recoveries varied. Samples were halved and sub-sampled; this process was repeated 3 more times with the retained sample. Sample was collected from the final sub-sample using a hand trowel; all sub-samples were placed in a 1-gallon container, which was then re-mixed and quartered. Aliquots were taken from each quarter to fill 3 sample containers. 1 sample was kept by CEC for moisture analyses, 1 sample was shipped to TN Tech for solids analyses, and the final sample was shipped to UGa for respirometric analyses.			(CEC, 2002a) pp. V-1 – V-12 Sample collection, processing, and analyses methods are described in App. D, Ch. 3	2	CEC provides a detailed write-up of the sampling procedure and rationale. Standard methods, or other well-recognized methods, were used for analyses. It is, however, unclear what was the particle size in the field-quartered material, and how large items were handled during the sub-sampling process. This raises some questions about possible sample bias.
i. sensors	NA			NA	NA	NA
ii. frequency	Approximately every 6 months	NA	Estimate	(CEC, 2002a) pp. V-1 – V-12	1	Confirmed by field logs of waste sampling (CEC, 2002c)
iii. field vs lab	Field sampling; lab preparation and analyses			(CEC, 2002a) pp. V-1 – V-12	1	NA
iv. incoming vs in-place	In-place			(CEC, 2002a) pp. V-1 – V-12	1	NA

v. moisture content	12/01 – 45.5 (avg., wet wt) 4/02 – 31.7 (avg., wet wt)	% %	Waste samples	(CEC, 2002a) pp. V-12 – V-14	3	The basis for these numbers is not known, nor is the quality known. Appendix E shows 5/3/02 trash moisture content averaging 80.75%; 5/8/02 samples range from 28.3 to 79.3%.
vi. volatile solids	21.45 avg. (10.15 to 45.92) – 7/00 17.28 avg. (4.14 to 49.89) - 8/10/00 19.06 avg. (12.51 to 27.74) – 11/00 19.11 avg. (5.34 to 34.03) – 12/00 23.40 avg.- 7/01	% % % % %	EPA Method 160.4	(CEC, 2002a) p. V-10 App. E	2	No QA data provided
vii. cellulose fraction	14.53 avg. (7.66 to 30.31) – 7/00 11.76 avg. (6.24 to 16.71) – 11/00 15.69 avg. (5.11 to 38.96) - 7/01	% % %	Gravimetric Method by Lossin (1971)	(CEC, 2002a) p. V-10 App. E	2	No QA data provided
viii. lignin fraction	7.87 avg. (3.98 to 17.08) – 7/00 6.25 avg. (4.26 to 11.23) – 11/00 6.44 avg. (2.85 to 13.79) – 7/01	% % %	Method by Effland (1977)	(CEC, 2002a) p. V-10 App. E	2	No QA data provided
ix. pH	NA	NA	NA	NA	NA	NA
x. BMP	199.23 (138.17 to 285.65) – 7/00 181.48 (121.03 to 234.72) – 11/00	Ml CH_4/g VS @ STP	Method by Owens and Chenowyth (1993)	(CEC, 2002a) p. V-10 App. E	2	Negative and positive controls were reported; the negative control was appropriately 0, but the value of the positive control (569.64) could not be evaluated.
xi. redox	NA	NA	NA	NA	NA	NA
xii. shear strength	NA	NA	NA	NA	NA	NA
xiii. compressibility	Unconfined Compressive Strength = 1338	Lbs/ft^2	Method number not specified	(HBA, 2002)	1	Standard soils test.
B. Waste mass - methods						

i. sensors	NA			NA	NA	NA
ii. frequency	NA	NA	NA	NA	NA	NA
iii. temperature	Varies with location, depth, and date. Weekly temperature profiles with depth were provided for 11 locations over 108 weeks. Temperatures generally range from 60 to 100 °F, with occasional swings up to 120 °F.	°F	170 Type T thermocouples	(CEC, 2002a) p. V-14 App. G	1	NA
iv. settlement	Dedicated settling pins are positioned along the plateau. These pins consist of seven (7) 18-inch sections of re-bar with plastic caps attached to one end of the bar. The re-bar was placed into the top of the bioreactor surface to the point where the capped end was facing up and flush with the original ground surface. The 18-inch length was chosen in order to limit the effects of bar movement due to frost heave. A random sampling scheme was used for determining the locations of the seven (7) settling pins. An initial survey was done 1/00. As of 4/17/00, the surface elevation has dropped 6 to 18 inches since bioreactor operation began, a 6,489 cubic yard decrease in overall volume. This is approximately 2.7% of the original volume over a 23-month period of operation. When normalizing for original volatile solids (22%), the volume reduction is expressed as the fraction of actual volume loss in the bioreactor relative to the fraction of TVS: i.e., [(6489 cy/242,000 cy)/0.22] x 100 = 12.19% volume reduction relative to volatile solids content.			(CEC, 2002a) p. V-17 App. H	2	Surface elevations and plots of elevation chages over time are presented in Appendix H. No additional information was provided to confirm data quality.

v. in-place volume	241,991 (1/00) 235,502 (4/02)	Yd^3	Engineering estimate based on surface surveys	(SSS, 2000) (SSS, 2002) (CEC, 2002a)	2	See I.2.A
vi. in-place density	51.7 (wet) 28.6 (dry) 1396 (wet) 772 (dry)	Lb/ft^3 Lb/yd^3	Shelby tubes and bag samples	(HBA, 2002)	1	See Appendix E of (CEC, 2002a)
vii. effective density	NA NA	NA	NA	NA	NA	NA
viii. water balance	No water balance performed; waste moisture content was performed on 1 sample: 80.8 (avg. for sample A2b)	% water	Shelby tubes and bag samples	(HBA, 2002)	1	See Appendix E of (CEC, 2002a)
C. Leachate – methods						
i. sensors	NA			NA	NA	NA
ii. frequency	Varies from weekly to quarterly, depending on constituent (see V.1.C.vi and vii below)	NA	NA	NA	NA	NA
iii. field vs lab	Both (see V.1.C.vii below)	NA	NA	NA	NA	NA
iv. in-place vs extracted	Extracted – individual grab samples (not composites) from LCS manhole and mix tank	NA	NA	NA	NA	NA
v. temperature	See V.1.C.vii below	NA	NA	NA	NA	NA
vi. head	4 (maximum – measured weekly to bi-weekly at 4 slope risers)	Inches	Gauge	(CEC, 2002a)	1	Visual confirmation
vii. composition	Field measurements with Oakton 10 pH/conductivity/temperature meter, a Cole Parmer ORP meter, and a YSI 550 DO meter. Comprehensive lab analyses quarterly.	NA	NA	(CEC, 2002a) p.V-20 App. L	3	Time series plots are provided, but lab analytical methods and QC data are absent
D. Liquids addition/recirculation – collection methods, frequency,	No separate sampling	NA	NA	(CEC, 2002a) p. V-20 Fig. 2a & 2b	2	Cumulative leachate input and leachate pump rate at various time intervals are

field vs. lab; temperature, composition						provided.
E. Gas – methods, sensors, frequency, field vs. lab, in-place vs. extracted; temperature, % O_2, % CH_4, % CO_2, % N_2 or balance, VOCs, NMOCs	Landtec GEM 500 – ever 2 weeks from monitor wells and randomly for vent wells - % O2, % CH4, % CO2, and % balance gases. Tedlar bag samples for first few months.	NA	NA	(CEC, 2002a) p.V-22 App I	2	Data, plus temporal graphs of GEM 500 constituents along with temperature were provided; no QC data.
F. Surface emissions – methods, sensors, frequency, field vs. lab; temperature, % O_2, % CH_4, % CO_2, % N_2 or balance, VOCs, NMOCs	Limited surface emissions data are available through April 2002. A copy of organic vapor data from an FID surface-testing event is included in Figure 8.0. Flux chamber testing to evaluate surface emissions may be initiated in the future.	NA	NA	(CEC, 2002a) p. V-23	3	Little data and no QC data provided
G Groundwater/lysimeters – methods, sensors, frequency, field vs. lab; composition	Semi-annual monitoring at 6 on-site wells, 3 on-site springs and 1 off-site well. Field parameters include pH, specific conductance, temperature, and turbidity. Lab parameters include VOCs chemicals called out in TDEC regulations.	NA	NA	(CEC, 2002a) p. V-23	3	No data provided
H. Climatologic – methods, sensors, frequency, on-site vs. off-site; temperature, barometric pressure, precipitation, wind speed, wind direction	On site weather station (Texas Weather Instruments), with a backup station at the adjacent Franklin Sewage Plant. Measures temperature, wind speed and direction, humidity, precipitation, barometric pressure, dew point, heat index, and wind chill. Remote access and data link.	NA	NA	(CEC, 2002a) p.V-29 App. J	2	No information provided on data quality
2. Operational Parameters or Constraints						
A. Moisture content goal or limitation	Maintain moisture content (based on total wet weight) in the 40% (minimum) to 60% (maximum) range. Composting literature recommends moistures in the 40 to 80% range;	%	NA	(CEC, 2002a) p.V-32 and Figure 9.0. Solid waste moisture vs.	2	No information provided on data quality

	however, concerns over limitations to air movement and oxygen mass transfer, especially at higher moisture contents, forces the operation to maintain moistures in the lower range of acceptable values.			pH is given in Figure 10.0		
B. Temperature operating range	The operation goal is to maintain temperatures near 60 degrees C, with an upper limit of 70 degrees C. The four leachate head riser pipes have been equipped with thermocouples placed at the liner surface.	NA	NA	(CEC, 2002a) p. V-32 App. G	2	Temperature plots for the liner and waste mass (at 4 depth intervals) were provided; temperature data quality cannot be determined
3. Closure Plan						
A. Phasing – immediate placement vs. delayed	The closure plan for the site is contingent on the final results of the bioreactor research at Williamson County. The Tennessee Division of Solid Waste Management will assess the final body of data for the site and will work with the County to produce an appropriate closure approach for the cell.	NA	NA	(CEC, 2002a) p. V-35	2	Closure plan not provided, but the general approach was confirmed by the regulatory agency
B. End-Use	The County is also considering the possibility of mining the residual contents of the cell once the bioreactor process has run its course. The mined residuals could be separated and processed for potential re-use as alternate cover soil or other regulatory-agency approved end use. The process of mining would remove the need for closure construction and post-closure monitoring for the bioreactor cell. If the site is not mined, the cell will be appropriately closed and will most likely be converted into part of the golf course planned for the overall landfill site.	NA	NA	(CEC, 2002a) p. V-35	3	No supporting data
4. Post-Closure Maintenance						
A. Final cover maintenance –	Periodic inspections of the cap will be	NA	NA	(CEC, 2002a)	3	No supporting data

inspections, frequency, settlement problems	performed in order to detect problem areas (e.g., breach in cap system, excessive settlement). In addition, seasonal re-seeding and fertilizing will occur until a healthy coverage of grass growth is achieved and maintained. Drainage structures will also be monitored to ensure that proper erosion-control is provided and that the flow path is kept open and appropriate slopes are maintained.			p. V-35		
B. Environmental monitoring – groundwater, leachate, gas	Groundwater and gas monitoring will be performed on a regular basis. Groundwater and gas wells are already installed and are currently being monitored on-site as part of the routine landfill compliance program.	NA	NA	(CEC, 2002a) p. V-40	3	No supporting data
C. Leachate collection and treatment	Leachate produced after closure will be collected via the current collection basins/sump systems and disposed by surface spraying (land application) for maintenance of the cover grasses and the grasses on the landfill golf course and/or by pumping and hauling of the leachate to a nearby wastewater treatment facility.	NA	NA	(CEC, 2002a) p. V-40	3	No supporting data
D. Gas extraction and use	NA – passive vents/no gas collection	NA	NA	NA	NA	NA
5. Problems Encountered and Resolution						
A. Excessive Temperatures or Fire (list and describe each event; use additional paper or copy report exerpts to describe)	To date, there have been no fires at the bioreactor site. Only one area, located near monitoring well 10, has reached temperatures near the allowable operating threshold of 70 degrees C. Additional leachate was injected into the “hot” area in an effort to control the	NA	NA	(CEC, 2002a) p. V-40	3	No supporting data

	temperature. The method appeared to work well for several days. However, the temperature began a steady increase thereafter. On May 3, 2002, the blowers were shut down in response to slope stability issues. After 20 hours, the “hot spot” near monitoring well 10 had dropped over 8 degrees C. There have been no other issues with excessive temperatures as of this date.					
B. Liquid distribution clogging (list and describe each event; use additional paper or copy report exerpts to describe)	There has been no evident clogging due to biological growth or sedimentation. Several injection wells have collapsed internally due to surrounding soil and waste pressures and due to undesirable well installation methods used by the contractor for this well system installation.	NA	NA	(CEC, 2002a) p. V-41	3	No supporting data
C. Ponding or seeps	None noted; leachate surcharge has been noted due to compressed air pressure and internal bioreactor gas pressure.	NA	NA	(CEC, 2002a) p. V-41	1	No surface ponding was noted during site visit; surcharging was noted with blowers off.
D. Leachate head > 1 ft	Based on data derived from the leachate head riser units, the maximum head measured to date has been approximately 4 inches. Refer to discussion in section V-1c.	Inches	Manual	(CEC, 2002a) p. V-42	3	No supporting data provided
E. Odors or gas migration	There has been no evidence of lateral gas migration at the site. There are odors emanating from the surface of the reactor. The odors are characteristic of leachate odors, including the sweet, pungent odors emanating from certain organic acids and propyl and butyl benzenes. There are also sulfide-based (“rotten-egg”) odors, as expected from hydrogen sulfide, mercaptans, and methanthiol. During the last sampling event, a heavy citrus odor from one of the borings was detected, which is	NA	NA	(CEC, 2002a) p. V-42	2	Minimal surface odors confirmed by site visit (although the compressors were operational only a short period of time); off-site gas migration could neither be confirmed nor denied.

	characteristic of limonene. None of the odors have been of such magnitude as to cause complaints from neighboring residents or personnel working at the site.					
F. Slope stability	See IV.4.A					
G. Cover integrity	The soil cover layer has remained in fairly good condition. The only exceptions to this are the areas where there have been veneer slope movements. In addition, the annular spaces along the wells have widened, most likely due to the initial wetted front from leachate injection and the high air pressures at the annual space of air injection wells. It is also worth noting that there have been several small holes that have been formed, in scattered locations, due to the force of the air being injected into the waste mass.	NA	NA	(CEC, 2002a) p.V-43	2	Small holes and general condition in isolated areas was confirmed by visual observation
H. Additional costs or resources – specialized equipment, materials, or personnel	Additional costs with the aerated bioreactor at Williamson County are associated with maintaining the blower system, pipe system, pumps, thermocouples, and storm water control structures. There have been many requirements related to general maintenance and repair. The operation of a bioreactor system requires constant attention and maintenance.	NA	NA	(CEC, 2002a) p.V-43	3	No supporting information available

Landfill Characterization Form - Crow Wing Bioreactor Landfill

FINALIZED DECEMBER 23, 2003

Bioreactor Landfills – State of the Practice Analysis

PARAMETER OR MEASURMENT TYPE	**MEASUREMENT OR OBSERVATION[1]**	**UNITS[2]**	**MEASUREMENT METHOD[3]**	**DATA SOURCE[4]**	**DATA QUALITY[5]**	**COMMENTS**
I. GENERAL						
3. Site Conditions	Complete A thru E below					
F. Address (include both mailing address, such as a P.O. Box, and facility address if different	Crow Wing County Solid Waste Office 301 Laurel Street, Complex West Brainerd, MN 56401-3522 (218) 842-1290					Site is 6 miles NE of Brainerd on Hwy. 210
B. Owner (name of county or municipal government, or private firm/owner)	Crow Wing County – contracted operation to a private firm					NA
F. Site History	Cell 1 (6.4 acres) constructed Fall 1991; filled 1996 Cell 2 (3.2 acres) constructed 1995; currently inactive Cell 3 (4.8 acres) constructed 2001; currently active Leachate recirculation began 4/98			(Beck, 2001b) (Beck, 2002a)	1	NA
G. Average disposal tonnage (annual or monthly)	34,009 (10-yr avg. from 1992 to 2001) (Range - 29,886 in 1992 to 39,054 in 2001	Tons/yr Tons/mo.	Waste receipts	(Beck, 2002b)	1	Annual report to Minnesota Pollution Control Agency (MPCA)
H. General area of refuse collection (describe the areal extent and land usage – industrial, light industrial, residential, etc.)	Crow Wing County - Mixed MSW - Light Industrial Waste			(Beck, 1998a) (Beck, 2000a) (Beck, 2001a)	1	Verified by 1999 and 2000 annual reports to the state regulatory agency

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
F. General Climate	Moderate summers and cold winters; annual rainfall of approximately 30 inches; ranged from 25.76 (1994) to 33.80 (2001), with avg. = 30.22 inches			(Beck, 2002b), Appendix E, Table 3	1	Annual report to MPCA
2. Bioreactor Project Background	Complete A thru E below					
A. General layout	*Complete i thru viii below; attach site diagram, if available*					
i. area – total or cell	14.4 Cell 1 = 6.4, Cell 2 = 3.2, & Cell 3 = 4.8	acres	Engineering design	(Beck, 2001b) (Beck, 1998a)	1	Cell 3 construction documentation; 22.5 acres permitted for 5 cells
ii. volume – total or cell	1,967,800 (permitted) 1,349,012 (remaining)	Yd^3	MPCA calculation format	(Beck, 2002b)	1	2001 Annual Report; includes daily/final cover
iii. depth – total or cell	90 ft	Ft	Survey	(Beck, 1998a)	1	Permit re-issuance document
iv. phase	Currently filling Cell 3			Visual observation	1	NA
v. module	NA			NA	NA	NA
vi. integration w/existing site	NA			NA	NA	NA
vii. new cell or retrofit	New			(Beck, 1998a)	1	Confirmed by visual observation
viii. test or full-scale	Full-scale			(Beck, 1998a)	1	Confirmed by visual observation
B. Project funding	County			NA	NA	NA
C. Period of operation	4 Cell 1 filled 1996 Cell 2 filled 2002 Cell 3 is active Re-circulation began 4/1998	Yrs		(Beck, 1998a) (Beck, 2001b) (Beck, 2002a)	1	Permit re-issuance
– full-time vs. demonstration	Demonstration			(Beck, 1998a)	1	Permit re-issuance
D. Primary goals and objectives	*Choose i thru vi below – describe*					

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
i. maximize settlement and effective density	Yes			Verbal – consultant for landfill	2	Not formally documented in writing, but appear to be consistent with operational mode
ii. minimize leachate disposal/treatment volume	Yes					
iii. increase gas production	Yes			Verbal – consultant for landfill	2	Not formally documented in writing
iv. reduce post-closure monitoring period	NA					
v. beneficial reuse of liquids	NA			NA	NA	NA
vi. other (explain)	Main goal is to demonstrate that a small landfill not required to control LFG (NSPS) can recover LFG for reuse			(Beck, 2002a)	1	NA
E. Permit approval process	Choose i thru iv below					
i. regulatory agencies (name agencies)	Minnesota Pollution Control Agency (MPCA)			NA	NA	NA
ii. regulatory exemptions (cite exemption)	None found in permit			(Beck, 1998a)	1	NA
iii. approval conditions	Leachate management Settlement measurements			(Beck, 2002b)	1	2001 Annual Report
iv. reporting requirements	Quarterly monitoring of leachate & LFG quantity & quality; & ambient air monitoring; semi-annual leachate Hg (ng/L) monitoring; and annual field capacity measurements			(MPCA, 2002a)	1	Final permit modification
II. HYDRAULIC CONTAINMENT						
1. Hydrogeology						
A. Top-most layer	*Repeat for each layer working from top to bottom*					
i. materials	Wisconsin outwash – sand with occasional lenses of till			(Beck, 1998b)	1	Site hydrogeologic investigation

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
ii. thickness	Information not provided	NA	NA			
iii. characteristics	Permeable					
iv. seasonal high water level	30 – (below the base of Cells 1 and 2)	feet	Water level measurements	(Beck, 1998b)	1	Site hydrogeologic investigation
B. Second layer from top	Wisconsin glacial till					
i. materials	No specifics provided					
ii. thickness	Information not provided					
iii. characteristics	Low permeability (10-8 to 10-9 cm/sec)					
iv. seasonal high water level	NA					
C. Third layer from top	Pre-Wisconsin glacial outwash (sand and silty-sand					
D. Fourth layer from top	Bedrock (Pre-Cambrian proterozoic argillite)					
4. Liner	Complete A thru E below					
A. Underlying geology or subbase (repeat for each layer starting with the top-most layer)	Complete i thru iii for each layer					
i. materials	• Composite liner constructed with 2 ft of compacted clay (K<10-7 cm/s) overlain with 1.5 mm smooth HDPE geomembrane. • The as-placed clay has LL = 29-39; PI = 13-21, P200 = 68-82%, and K = 2.8E-9 – 2.7E-8 cm/s/			(Beck, 1998a) (Beck, 1996) (Beck, 2001b)	1	Permit documents and construction documentation reports

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	• NW geotextile cushion is on top of GM (340 g/m2) only in the leachate collection trenches; sand on top of GM in all other locations. • Liner detail in Attachment A.					
3. Leachate Collection Layer						
A. Drainage Layer(s)	*Complete i thru iii for each layer*					
i. materials	Collection layer is sand with gravel adjacent to collection pipes. Sand is 305 mm thick, SP, Cu = 3.5-4.4, P200 = 5.0-5.5%, and K = 2.6E-2 - 3.3E-2 cm/s. LCS detail in Attachments A and B			(Beck, 1996)	1	Construction Documentation Report
B. Lysimeters – number	Lysimeters installed beneath leachate collection lines. Lined with 22 ft wide HDPE geomembrane (1.5 mm, smooth) bedded on natural sand subgrade. Perforated 100 mm HDPE pipe is used to collect the liquid via pump (cell 3) or by gravity (cells 1 and 2). See Attachments A and B.			(Beck, 1996)	1	Construction Documentation Report
4. Leachate Collection and Disposal	Complete A thru H below					
A. Components of leachate collection	*Describe each component in i thru v below*					

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
i. piping layout/spacing (attach diagram if available)	LCS pipes run longitudinally through cell at 100 ft spacing. Pipes are bedded in 18 in thick gravel pack wrapped in a non-woven geotextile. Pipe is 150 mm HDPE with 12 mm perforations spaced at 125 mm. Perforations are at quarter points along circumference of pipe, with orthogonal perforations staggered longitudinally along pipe. Gravel has 100% finer than 19 mm and 98% coarser than 4.8 mm. See Attachment A.			(Beck, 1996)	1	Construction Documentation Report
iii. sumps – number/design (describe each if different – attach diagrams if available)	Each cell has a single sump. Header moved water from each leachate collection line to the sump.			(Beck, 1996)	1	Construction Documentation Report
iv. pumps – number/design (describe each if different – attach diagrams if available)	Cells 1 and 2 use a gravity drainage system to an exterior vault. A pump then returns the leachate via a force main to the recirculation system or to leachate treatment ponds. Cell 3 has an internal sideslope riser sump that pumps water to the same vault as Cells 1 and 2 drain.			(Beck, 2002a)	1	Recirculation-to-Energy Report – the site permit has been amended to include this design/data
v. collection areas	See Table 3 (attached)	NA	NA	(Beck, 2002b)	1	2001 Annual Report to MPCA
B. Collection frequency	Continuous	NA	NA	NA	NA	NA
C. Volume collected	21,186,864 (1992 – 2001)	Gallons	Meters	(Beck, 2002b)	1	2001 Annual Report to MPCA
D. Collection rate	2,118,686 (avg.)	Gallons/yr	Calculation	(Beck, 2002b)	1	2001 Annual Report to MPCA
E. Disposal methods – sanitary, on-site treatment, recirculation,	- Sanitary – MCES (1992 – 1997); BPUC (2002)			(Beck, 2002b)	1	2001 Annual Report to MPCA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
haul off-site, evaporation	- Land Applied (1995 – 2002) – old fill - Recirculated (1997 – 2002)					
F. Disposal frequency	No liquid is currently being disposed. All is land applied or recirculated.	NA	NA	NA	NA	NA
G. Disposal volumes	8,964,150 (total – MCES) 11,822,678 (total – land applied) 3,608,284 (total recirculated) All numbers are 1992 – 2001; pond evaporation not accounted for	Gallons Gallons Gallons	Meter	(Beck, 2002b)	1	2001 Annual Report to MPCA
H. Disposal rates	1,494,025 (MCES, 6-yr avg.) 1,970,446 (Land Apply, 6-yr avg.) 893,071 (Recirc., 4-yr avg.) • Land Apply does not include startup of 24,000 gal in 1995 • Recirc does not include 36,000 gal in 1997 (startup)	Gal/yr Gal/yr Gal/yr	Calculation	(Beck, 2002b)	1	2001 Annual Report to MPCA
3. Liquids Addition						
A. Liquid sources – leachate, wastewater, surface water, sludge (type and % solids), groundwater (describe – if multiples, designate each as 1, 2, 3, etc.)	1. Leachate 2. Stormwater collected in ponds is not recirculated; the only stormwater entering the landfill is precipitation directly on the active fill area (stormwater treatment pond sludge is added to landfill)			(Beck, 2002a)	1	Recirculation-to-Energy Report – the site permit has been amended to include this design/data
B. Methods of liquid addition – surficial spraying, horizontal pipes/trenches, vertical injection wells, infiltration	Raw leachate is recirculated from the vault via a force main to recirculation lines. When land application cannot be conducted, treatment pond water is also			(Beck, 2002a)	1	Recirculation-to-Energy Report – the site permit has been amended to include this design/data

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
ponds (describe)	recirculated. Pond water applied to top of Cells 1-2 in uncapped area over a layer of green waste via spray application. Also will spray apply to working face in future. Currently all recirculation is via buried recirculation lines, except spray application to yard waste area. As much liquid as possible is recirculated in attempt to minimize more costly land application and treatment plant options.					
i. Application frequency (each source)	Typically 1-2 days per line is required to reach average dosage of 22 gall/ft. Then RL is moved to next line. Continue to sequence through lines. Spray on top was conducted about twice weekly from Aug 27-Oct 9 2002 with approx same amount applied each time.	Times/day	Estimate	(Beck, 2002a), (Doran, 2003)	1	Recirculation-to-Energy Report – the site permit has been amended to include this design/data
ii. Application rates (each source)	18 to 32 gal/ft (240 to 420 L/m) of perforated pipe. Average is 22 gal/ft or 289 L/m. Actual dosage data from 2002 are in Attachment C	Gal/min				
iii. Daily application volumes (each source)	Total volumes for 2002 are summarized in Attachment C. Total spray applied was 498,742 gall	Gallons	Estimate	(Beck, 2002c) (Doran, 2003)	2	Summary document prepared for this project by Fred Doran
G. System components – general (describe and complete i thru viii below)	Recirculation lines are constructed from 4 and 5 in HDPE perforated pipe. Two diameters are used to provide a slip fit between pipes that allows sections to distort with settlement without breaking. Lithium grease is			(Beck, 2002a) (Doran, 2003)	1	Recirculation-to-Energy Report – the site permit has been amended to include this design/data

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	applied at pipe junctions. There is a 3 ft overlap between sections. Perforation size and spacing are shown on Attachment D. Perforation diameter varies along pipe so that leachate is more uniformly distributed along pipe (more perforation on downstream end). Pipes are sloped at 1% and contain 50 ft solid sections on either end to prevent seeps.					
ix. spacing	20 ft vertical, 50 ft horizontal. There are two sets of pipes installed corresponding to two elevations.	NA		(Beck, 2002a) (Doran, 2003)	1	Recirculation-to-Energy Report – the site permit has been amended to include this design/data
x. backfill material/ characteristics	Backfill consists of a 2 ft x 2 ft box of 6 in nominal tire shreds covered with a NW geotextile			(Beck, 2002a) (Doran, 2003)	1	Recirculation-to-Energy Report – the site permit has been amended to include this design/data
xi. automation (describe; include schematics if available)	All recirculation lines are hard plumbed to leachate management system via a force main. Valving is manual. All pipes are now insulated and heat traced to permit recirculation during sub-freezing weather. Flow meters record volume dosed to each pipe.			(Beck, 2002a) (Doran, 2003)	1	Recirculation-to-Energy Report – the site permit has been amended to include this design/data
4. Intermediate Cover Application						
A. Cover layer materials (list each as 1, 2, 3, etc.)	A layer of miscellaneous sandy fill approx 12 in thick is used for interim cover. No grass. Was seeded but killed by gas.			(Beck, 2002a) (Doran, 2003)	1	Recirculation-to-Energy Report – the site permit has been amended to include this design/data
5. Final Cover Design						
A. Gas collection or grading layer (describe and complete i thru iv)	Cover, from bottom to top: 12 in of local sand (interim cover), 6 in compacted sand (same as LCS), LLDPE 1.0 mm textured geomembrane, geocomposite drainage			(Beck, 2002a) (Beck, 1997) (Doran, 2003)	1	Recirculation-to-Energy Report 1997 Cell 1 Final Cover Construction Documentation Report by

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	layer, 18 in rooting zone, 6 in vegetated topsoil.					RW Beck Personal Conversation
F. Cover placement to date – area	Cell 1 was completely covered. However, large settlements occurred on north end where recirculation was occurring. Cover was removed on top deck (approx 35% of total area) for additional filling. No other cover placed to date.	NA	NA	(Beck, 2002a) On site observation	1	Recirculation-to-Energy Report
i. vegetative growth – type	Weak grass on side slopes			On site observation	1	NA
G. Components of surface water collection system – berms, piping/structures, basin	None in place.			NA	NA	NA
III GAS MANAGEMENT						
1. Air Injection						
A. Methods of air injection –	No air injection			NA	NA	NA
2. Gas Extraction						
A. System components	Gas collection is passive through three vertical wells installed in Cell 1 (no vents are yet installed in Cells 2 & 3). Perforated CPVC with gravel backfill. Bentonite plug at surface with soil overburden. See Attachment E for detail.	NA	NA	(Beck, 2002a)	1	Recirculation-to-Energy Report
B. Gas extraction frequency	Passive. Flows are monitored intermittently. See Appx. D of Beck 2002a for data	NA	NA	(Beck 2002a)	1	Recirculation-to-Energy Report
C. Efficiency of extraction system – migration, odors, collection area/influence, areal variability	No unusual odors.			On site observation	2	NA – short duration of site visit does not provide full support to this observation.

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
D. Post collection uses – flare, gas-to-energy, industry	None, but gas to energy plant is being considered if gas quality and quantity proves adequate.			(Beck, 2002a) (Doran, 2003)	1	Recirculation-to-Energy Report
IV. WASTE MANAGEMENT						
1. Incoming Waste Categories and Percentages						
A. MSW breakdown	*Describe and list percentages in I thru vii*	99.8 % of total		(Beck, 2001a)	1	2001 Annual Report to MPCA
i. paper and cardboard	NA	%	NA	NA	NA	NA
ii. plastics	NA	%	NA	NA	NA	NA
iii. metal	NA	%	NA	NA	NA	NA
iv. wood	NA	%	NA	NA	NA	NA
v. food waste	NA	%	NA	NA	NA	NA
vi. yard waste	NA	%	NA	NA	NA	NA
vii. other	Used oil, lead acid batteries, tires, appliances, yard waste, and demolition debris are recycled or otherwise handled – not landfilled	NA	NA	Visual confirmation when on site	1	NA
B. Industrial waste (describe)	<10 (since 1991)	%	Unknown	(Beck, 2002a)	3	NA
C. Special waste (describe)	671 - bag and bulk asbestos (10 years from 1992 – 2001)	tons	Total from weigh tickets	(Beck, 2002b)	1	2001 Annual Report to MPCA
D. Liquids (list and describe)	NA	NA	NA	NA	NA	NA
E. Sludges (list and describe)	Sludges from the leachate treatment	NA	NA	NA	NA	NA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	ponds are deposited in the landfill					
2. Incoming Waste Processing						
A. C&D, transfer vs. direct disposal	Direct – commercial haulers plus self drop C&D waste is separated into another landfill site.	NA	NA	(Beck, 2002b)	1	Visual confirmation during on site visit
B. Pre-placement processing						
i. shredding	None			NA	NA	NA
ii. mixing	None			NA	NA	NA
iii. chemical or nutrient adjustment	None			NA	NA	NA
C. Waste placement						
i. compactive effort	CAT 826C compactor used to distribute and compact trash into 10-foot lifts. Slope lift to center to promote inflow of SRO	NA	NA	Visual observation	1	Landfill operator believed that inward slope was critical to preventing seeps and maintaining side slope stability
ii. size of active area	Open area (not yet closed) varies between 6.4 and 9.64 acres (currently 7.77 acres – cells 2 and 3, plus re-opened cell 1); active face is several hundred square feet	NA	NA	(Beck, 2002b)	1	Visual observation of active face
iii. lift thickness	10	Feet	NA	Verbal	2	Generally confirmed by visual observation
iv. moisture addition	None except via recirculation system; will be adding moisture to the working face in new cell; 5,000 to 10,000 gallons/day	NA	NA	Verbal	3	No supporting data
3. Daily Cover Application and Odor Control						

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
A. Methods of daily cover – tarps, soil, foam, select waste (e.g., foundry sand), spray covers	ConCover (spray) and local sand	NA	NA	(Beck, 2002a) (Doran, 2003)	1	Recirculation-to-Energy Report
i. application frequency	Daily: Monday through Friday – ConCover; Saturday – local sand cover 6 in	NA	NA	(Beck, 2002a)		
ii. application rates	ConCover - ADC - placed on top of each 3m lift	NA	NA	(Beck, 2002a)		
iii. thickness	6 (sand)	Inches	Estimate	(Doran, 2003)	3	No supporting data
iv. removal and reuse	No removal	NA	NA	(Doran, 2003)	3	No supporting data
B. Other odor controls – liquid additives, gas extraction, spray covers, misting systems, neutralizing vs. masking	Gas venting	NA	NA	Verbal confirmed by visual observation	1	NA
4. Geotechnical Properties and Stability						
A. In-place controls – sloping, buttressing, geosynthetic reinforcement, moisture limitations	None. Conventional stability analysis indicates no special provisions required	NA	NA	(Beck, 2002a)	1	Recirculation-to-Energy Report
B. Field observations – sloughing, differential settlement, new waste vs. degraded waste behavior	Differential Settlement	NA	NA	On-site observation	1	NA
C. Seismic considerations	NA	NA	NA	NA	NA	NA
V. LANDFILL/ BIOREACTOR OPERATION AND CONTROL						
1. Monitoring						

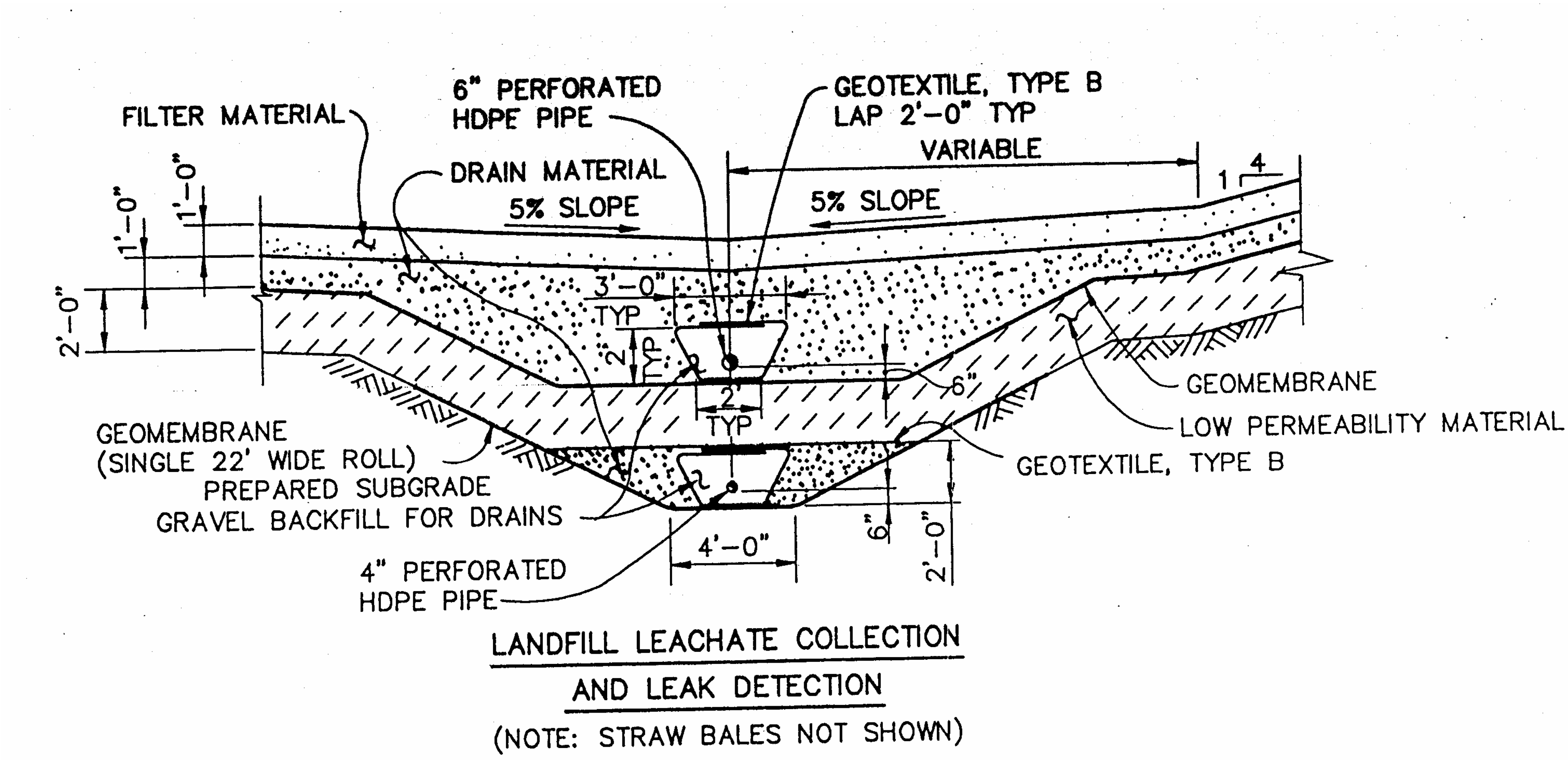
PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
A. Waste solids	NA	NA	NA	NA	NA	NA
i. sensors	NA			NA	NA	NA
ii. frequency	NA	NA	NA	NA	NA	NA
iii. field vs. lab	NA			NA	NA	NA
iv. incoming vs. in-place	NA			NA	NA	NA
v. moisture content	NA	NA	NA	NA	NA	NA
vi. volatile solids	NA	NA	NA	NA	NA	NA
vii. cellulose fraction	NA	NA	NA	NA	NA	NA
viii. lignin fraction	NA	NA	NA	NA	NA	NA
ix. pH	NA	NA	NA	NA	NA	NA
x. BMP	NA	NA	NA	NA	NA	NA
xi. redox	NA	NA	NA	NA	NA	NA
xii. shear strength	NA	NA	NA	NA	NA	NA
xiii. compressibility	NA	NA	NA	NA	NA	NA
B. Waste mass - methods	NA	NA	NA	NA	NA	NA
i. sensors	NA			NA	NA	NA
ii. frequency	NA	NA	NA	NA	NA	NA
iii. temperature	NA	NA	NA	NA	NA	NA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
iv. settlement	4 settlement plates plus 8 other survey points	%	Ground Survey	(Beck, 2002b)	1	2001 Annual Report to MPCA
v. in-place volume	618,771 (2001 – from top of drainage layer to waste surface)	Yd^3	Ground Survey	(Beck, 2002b)	1	2001 Annual Report to MPCA
vi. in-place density	881 (1996) 1051 (1997) 1055 (1998) 1243 (1999) 1402 (2000) 1562 (2001)	AUF	Calculation (pounds disposed divided by yd^3 utilized)	(Beck, 2002b)	1	2001 Annual Report to MPCA
vii. effective density	NA	NA	NA	NA	NA	NA
viii. water balance	No – plan to measure field capacity per permit requirements	% water	Saturation at 1200, 1400, & 1600 lb/yd^3 density; % water when drainage stops	(Beck, 2002b)	2	Not yet performed; some discussion of trying to eliminate this test
C. Leachate – methods	COD/BOD PH VOCs Metals Chloride Other – too numerous to list	NA	NA	(MPCA, 2002a)	1	NA
i. sensors	Pressure transducers in each cell (sump) for leachate head Thermocouple in cell 3			(Beck, 2002a)	1	Recirculation-to-Energy Report
ii. frequency	Quarterly – compliance Monthly – system operation	NA	NA	(Beck, 2002b)	1	NA
iii. field vs. lab	Lab	NA	NA			
iv. in-place vs. extracted	Extracted	NA	NA	NA	NA	NA
v. temperature	None (a thermocouple in Cell 3 sump has recorded data since ½; starting temperature was mid-50's; currently in	°F	Thermocouple	NA	NA	NA

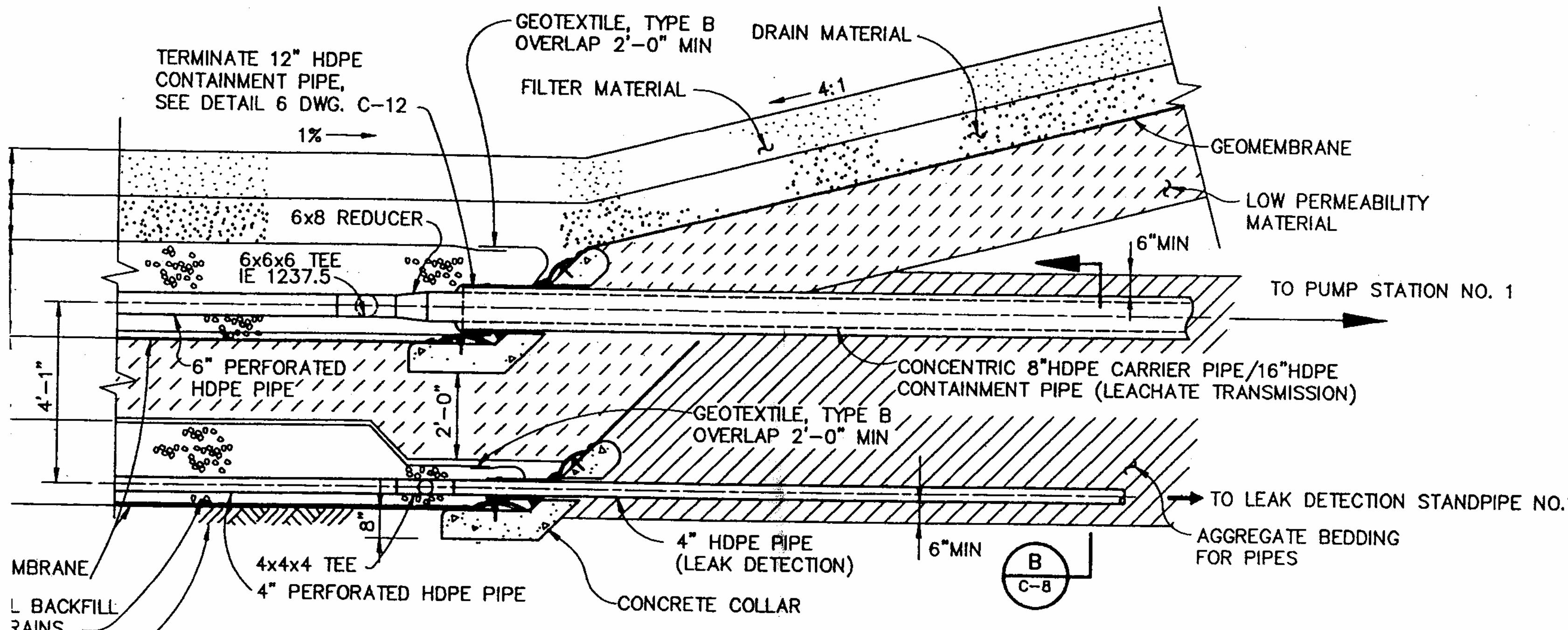
PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	the 70's (F) with no recirculation.					
vi. head	Alarm sounds if exceeds 305 mm	Inches	Pressure transducer	(Beck, 2002a)	1	Recirculation-to-Energy Report
vii. composition	COD – 2164 (avg.; 1400 to 3000) BOD – 582 (avg.; 60 to 1700) pH – 7.5 (typical; 6.5 to 8.2) Chloride – 1500 (typical; 0 to 2000) Total VOCs – (range 2,000 to 3,200)	mg/L mg/L unitless mg/L µg/L	Lab methods for 11 samples in 2001	(Beck, 2002b)	1	Original data sheets and summaries reviewed.
D. Liquids addition/recirculation – collection methods, frequency, field vs. lab; temperature, composition	NA	NA	NA	NA	NA	NA
E. Gas – methods, sensors, frequency, field vs. lab, in-place vs. extracted; temperature, % O_2, % CH_4, % CO_2, % N_2 or balance, VOCs, NMOCs	O_2 – field (monthly) - lab (annual with CO_2, Ar, & N) CH4 – field (monthly) - lab (annual) Velocity (field - to calculate flow using pipe diameter) VOCs – lab	% % v/v % % v/v mph ppbv	Portable gas meter ASTM D1945 Portable gas meter ASTM D1945 Turbometer TO-14	(Beck, 2002b)	2	Lab analytical sheets provided; no QA data
F. Surface emissions – methods, sensors, frequency, field vs. lab; temperature, % O_2, % CH_4, % CO_2, % N_2 or balance, VOCs, NMOCs	Quarterly in field - 100 ft by 100 ft grid - monitor O2 and CH4 - plan to monitor organic vapors	 % %	 Portable meter OVA	(Beck, 2002b) Verbal	3	No data available
G Groundwater/lysimeters – methods, sensors, frequency, field vs. lab; composition	Semi-annual (annual for some constituents) - VOCs - Metals - Cations – too numerous to list - Anions – too numerous to list - TDS/TSS - NH3 - Alkalinity	NA	NA	(Beck, 2002b)	2	Data summary tables and QA (duplicates and trip blanks) provided in separate data files
H. Climatologic – methods, sensors, frequency, on-site vs.	Monthly - Temperature	Weather station	Local DNR weather site approximately 1	(Beck, 2002b)	3	No data provided

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
off-site; temperature, barometric pressure, precipitation, wind speed, wind direction	- Barometric Pressure - Wind speed and direction - Precipitation		mile away On site measurement			
2. Operational Parameters or Constraints						
A. Moisture content goal or limitation	< Field capacity	%	Drainage of free liquid from waste samples	Verbal	3	No data
B. Temperature operating range	Not established– thermocouple in cell 3 is operational (50 to 70 F without recirculation)	NA	NA	NA	NA	NA
3. Closure Plan						
A. Phasing – immediate placement vs. delayed	Delayed pending settlement	NA	NA	NA	NA	NA
B. End-Use	Green space	NA	NA	NA	NA	No specific written plan
4. Post-Closure Maintenance						
A. Final cover maintenance – inspections, frequency, settlement problems	Standard Subtitle D	NA	NA	NA	NA	NA
B. Environmental monitoring – groundwater, leachate, gas	Standard Subtitle D	NA	NA	NA	NA	NA
C. Leachate collection and treatment	Standard Subtitle D	NA	NA	NA	NA	NA
D. Gas extraction and use	Standard Subtitle D	NA	NA	NA	NA	NA
5. Problems Encountered and Resolution						
A. Excessive Temperatures or Fire (list and describe each event; use additional paper or copy report excerpts to describe)	1 fire at active face on 4/29/01; independent of BRLF	NA	NA	(Beck, 2001b)	1	NA

PARAMETER OR MEASURMENT TYPE	**MEASUREMENT OR OBSERVATION**[1]	**UNITS**[2]	**MEASUREMENT METHOD**[3]	**DATA SOURCE**[4]	**DATA QUALITY**[5]	**COMMENTS**
H. Liquid distribution clogging (list and describe each event; use additional paper or copy report excerpts to describe)	None documented; routine cleanouts through quick-connects. Formation of leachate rock (iron sulfide) due to foaming at inlet; leachate rock formed downgradient of pump station; added drop pipe to eliminate turbulence.	NA	NA	Verbal	3	NA
C. Ponding or seeps	Seep on north face (old haul road) – discontinued leachate recirculation and used backhoe to break up compacted road base and seep disappeared	NA	Observed by site operator on 5/30/01 – 11 inches of rain fell in April and May	(Beck, 2001b)	1	None noted when on site – recirculation ongoing
D. Leachate head > 1 ft	No. transducers at the base of Cells 1 and 3 show levels within trenches, well below the liner elevation.	NA	NA	Verbal	3	NA
E. Odors or gas migration	CH4 at buildings < 10 No odors	% LEL	Portable meter	(Beck, 2001b)	1	None noted when on site – recirculation ongoing
F. Slope stability	5:1 installed	NA	NA	(Beck, 1998a)	1	NA
G. Cover integrity	NA – final cover not installed over most of area. Slope areas of Cell 1 that are covered appear fine.	NA	NA	On site inspection.	NA	NA
H. Additional costs or resources – specialized equipment, materials, or personnel	Basic cap – $200 to $300 K Laterals - $10K	NA	NA	Verbal	3	NA


6" PERFORATED
HDPE PIPE
FILTER MATERIAL
GEOTEXTILE, TYPE B
LAP 2'-0" TYP
VARIABLE
DRAIN MATERIAL
5% SLOPE
5% SLOPE
1'-0"
1'-0"
2'-0"
1
4
3'-0"
TYP
2' TYP
2'
TYP
6"
GEOMEMBRANE
LOW PERMEABILITY MATERIAL
GEOTEXTILE, TYPE B
GEOMEMBRANE
(SINGLE 22' WIDE ROLL)
PREPARED SUBGRADE
GRAVEL BACKFILL FOR DRAINS
4" PERFORATED
HDPE PIPE
4'-0"
6"
2'-0"
LANDFILL LEACHATE COLLECTION
AND LEAK DETECTION
(NOTE: STRAW BALES NOT SHOWN)

ATTACHMENT B – LSYIMETER



LEACHATE COLLECTION AND LEAK DETECTION PIPE PENETRATIONS
(NOTES: FOR ADDITIONAL INFORMATION SEE DETAIL 4, THIS DWG.
STRAW BALES NOT SHOWN)

DETAIL 3

SCALE: 3/8"=1'–0"

TABLE 3 HISTORIC LEACHATE GENERATION RELATIVE TO PRECIPITATION AND SITE DEVELOPMENT						
Year	Precipitation * County AV (in)	Open Area (acres)	Closed Area (acres)	Precipitation Into Open Area (gallons)	Total Leachate Generated (gallons)	% Retained In Waste
1992	26.44	6.4	0	4,614,661	1,902,452	59%
1993	29.06	6.4	0	5,071,739	2,178,057	57%
1994	25.76	6.4	0	4,495,979	1,631,822	64%
1995	34.52	6.4	0	6,024,891	2,211,956	63%
1996	28.47	9.64	0	7,453,446	2,750,771	63%
1997	27.23	7.35	2.29	5,435,680	2,575,634	53%
1998	31.95	7.35	2.29	6,377,891	2,154,290	66%
1999	33.72	7.35	2.29	6,731,220	1,977,458	71%
2000	31.24	7.77	1.87	6,590,832	1,722,929	74%
2001	33.80	7.77	1.87	7,130,926	2,081,451	71%
TOTAL	302.19			59,927,265	21,186,820	65%
* Source: State Climatology Office, Division of Waters, Minn DNR						

(Beck, 2002b)

ATTACHMENT C – SUMARY OF RECIRCULATION DATA

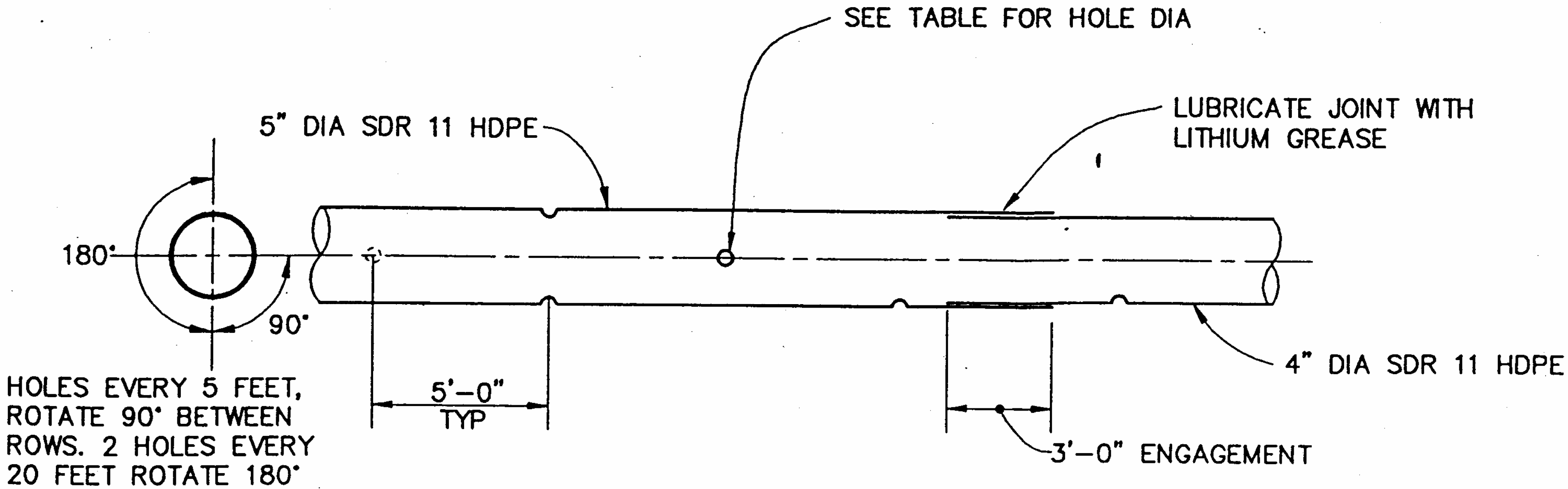
Table 4
2002 Recirculation Dosing Volumes
(gallons)

Recirculation Lateral	Apr	May	Jun	Aug	Sep	Oct	Nov	Dec	Total	Perforated Trench Length (ft)	Leachate Loading (gal/ft)
RL 1	89,092 (7)	95,080 (9)	18,422 (2)	0	26,796 (3)	0	24,379 (2)	28,687 (3)	282,456 (26)	452	24.0
RL 2	65,767 (7)	103,860 (9)	17,498 (2)	0	14,450 (2)	0	22,099 (2)	31,687 (3)	255,351 (25)	504	20.3
RL 3	61,017 (6)	95,173 (9)	24,755 (3)	0	24,124 (3)	0	10,820 (1)	34,950 (4)	250,839 (26)	515	18.7
RL 4	47,233 (6)	99,373 (9)	0	0	23,522 (3)	0	9,466 (1)	19,146 (3)	198,740 (22)	543	16.6
RL 5	72,147 (7)	91,289 (9)	24,060 (2)	0	32,368 (4)	0	23,609 (2)	33,983 (3)	277,456 (27)	315	32.6
RL 6	55,219 (6)	91,295 (9)	32,686 (3)	0	22,698 (3)	0	24,365 (3)	26,796 (3)	253,059 (27)	388	24.2
RL 7	65,733 (6)	98,160 (9)	30,467 (3)	0	28,798 (3)	0	11,004 (1)	25,200 (3)	259,362 (25)	505	20.5
ML	0	0	0	65,970 (2)	200,898 (7)	231,874 (5)	0	0	498,742 (14)	NA	NA
Total	456,208	674,230	147,888	65,970	373,654	231,874	125,742	200,449	2,276,015 (192)		

( ) = number of lateral dosing cycles

ML = Mobile Lateral: Spray application of leachate on yard waste placed on top of the Cell 1 and 2 intermediate crown

ATTACHMENT D – RECIRCULATION LATERIAL DETAIL



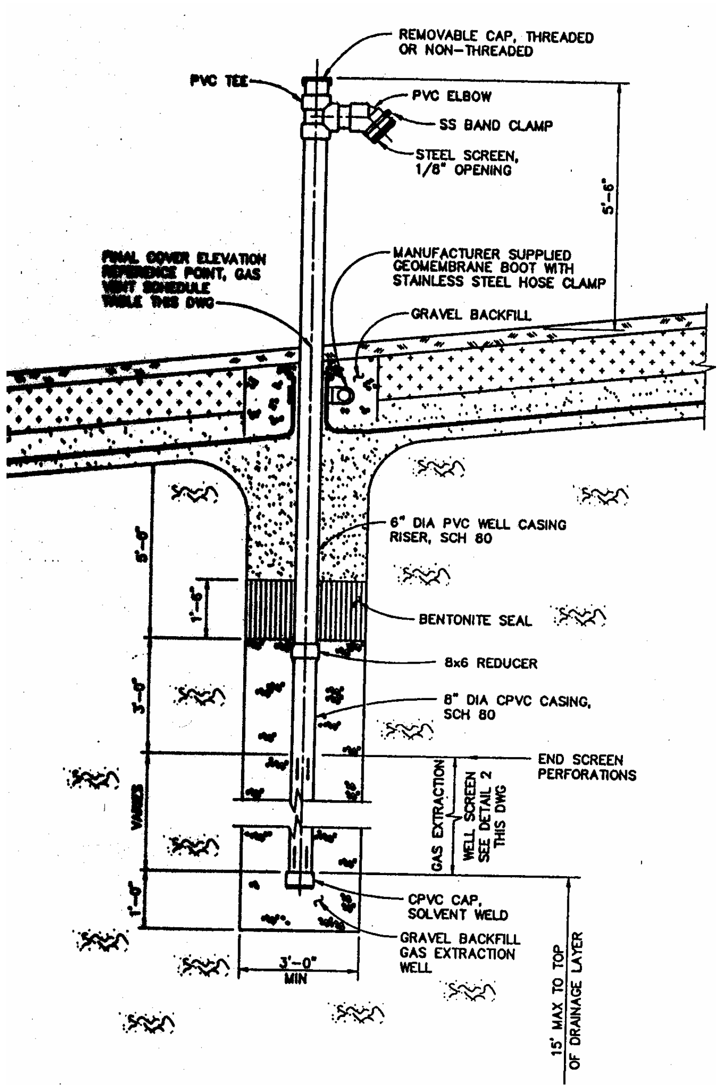
RECIRCULATION LATERAL PERFORATIONS

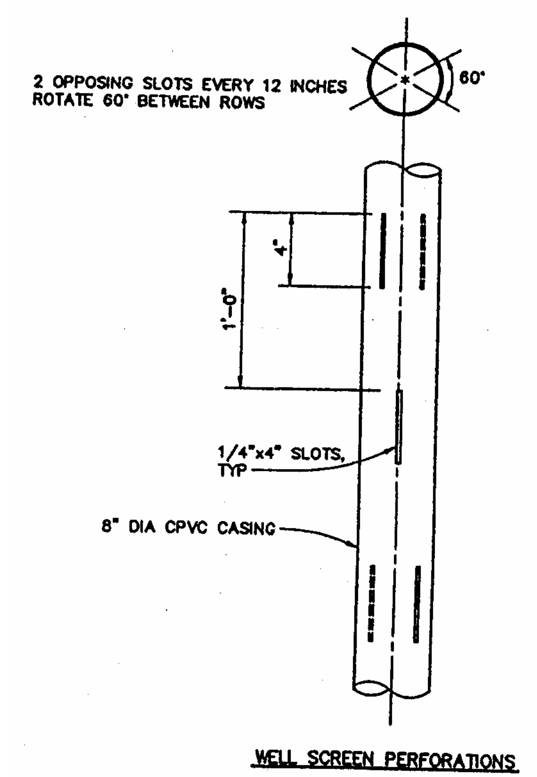
DETAIL 2 / –

NO SCALE

PERFORATED LENGTH OF RL FROM EAST	PERFORATION HOLE DIAMETER (IN)
0–120'	1/4
120–240'	5/16
240–360'	3/8
360–480'	7/16
480–600'	1/2

ATTACHMENT E – GAS WELL DETAIL





Landfill Characterization List – DSWA CSWMC

FINALIZED DECEMBER 29,2003

Bioreactor Landfills – State of the Practice Analysis

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
I. GENERAL						
5. Site Conditions	*Complete A thru E below*					
I. Address (include both mailing address, such as a P.O. Box, and facility address if different	Central Solid Waste Management Center Sandtown, DE					
B. Owner (name of county or municipal government, or private firm/owner)	Delaware Solid Waste Authority (DSWA) – state authority set up to manage solid waste					DSWA 1128 S, Bradford St. Dover, DE 19903
I. Average disposal tonnage (annual or monthly)	120,000 - average 71,311 to 137,968 - range 228 to 441 (avg./ operating day)	Tons/yr Tons/yr Tons/day	Based on tipping records – reported in facility fact sheet	(CSWMC, 2001) p. 2	2	No tipping records requested/ provided
J. General area of refuse collection (describe the areal extent and land usage – industrial, light industrial, residential, etc.)	Kent County – population of approximately 111,000			(CDM, 1997b) p. 1-1	2	Based on the facility operating plan – not PE-certified
K. General climate Information	The mean monthly temperature ranges from 34^{O}F in January to 77 ^{O}F in July. Average monthly precipitation ranges from 2.9 inches (February) to 4.3 inches (August).	NA	NA	(www.weather.com)	1	NA
2. Bioreactor Project Background	*Complete A thru E below*					
A. General layout	Complete i thru viii below; attach site					

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	diagram, if available					
i. area – total or cell	C/D Valley –6.5 Area D – 24 Area E- 34	Acres Acres Acres	Based on design drawings	(CSWMC, 2001) p. 1	2	No basis provided
ii. volume – total or cell	C/D Valley – 190,000 (estimated) Area D – NA Area E – 3,839,300 (estimated)	Yd^3 Yd^3	Design	(CDM, 1997a)	2	Appendix A not provided to show calculations; Area D volume not provided
iii. depth – total or cell	NA	NA	NA	NA	NA	Information not provided.
iv. phase	Leachate recirculation is currently occurring at C/D Valley and Area D; Area E is designed for leachate recirculation and will reportedly begin to receive leachate (on completed/capped sections) as soon as regulatory approval is received			(Schnabel, 1997) (CDM, 1997b) (CDM, 2002) p.3-1	2	The PE-certified Engineering Report (CDM, 1997a) and the Operations Plan (CDM, 2002) discuss horizontal injection trenches (HIT) for leachate recirculation in C/D Valley and Area E. No “as builts” or construction certification was provided for Area D
v. module	NA			NA	NA	NA
vi. integration w/existing site	Overlay/contiguous			NA	NA	NA
vii. new cell or retrofit	New			(CSWMC, 2001)	1	Confirmed by PE-certified “As Builts”
viii. test or full-scale	Full-scale; no control cell			(CSWMC, 2001)	1	Confirmed by PE-certified “As Builts” and visual observation
B. Project funding	Public			(CSWMC, 2001) p. 1	3	No supporting information provided
C. Period of operation	Waste placement in: Area A/B:10/80 –10/88 8 Area C: 10/88 – 12/93 5 Area D: 10/93 – 6/98 5	 Yrs Yrs Yrs	NA	Various	2	Information pieced together from several sources; no comprehensive overview

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	C/D Valley: 6/98 – 6/99 1 Area E : 6/99 – present 3 Active gas extraction began in Areas A/B, C, and D in 8/96.	Yrs Yrs				available to confirm consistency among sources
– full-time vs. demonstration	Full-time			(CDM, 1997b) Sections 1 & 2	2	NA
D. Primary goals and objectives	Choose I thru vi below – describe					
i. maximize settlement and effective density	Surface surveys are performed monthly to estimate compaction density and side slopes.			Conversations with the Engineering Manager and Chief Engineer	3	No supporting information provided.
ii. minimize leachate disposal/treatment volume	Leachate disposal has decreased during the last 3 years.					
iii. increase gas production	Accelerated gas production may reduce very long-term post-closure care.					
iv. reduce post-closure monitoring period	Post closure care is affected dramatically by leachate treatment cost.					
v. beneficial reuse of liquids	None identified					
vi. other (explain)	Maximize waste degradation which will, in turn, reduce the long-term risk from, and associated costs for managing and treating leachate and gas produced from that waste. There would also be less dependence on long-term liner performance to minimize environmental risks. Finally, waste mining is a potential approach to recover certain items (metal, glass, etc.) and to reuse land space (there does not currently appear to be an economic driver to do this).					

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
E. Permit approval process	*Choose I thru iv below*					
i. regulatory agencies (name agencies)	State of Delaware, Department of Natural Resources & Environmental Control (DNREC)			Meetings with Solid Waste Management Branch	1	Met with hydrogeologist responsible for the Central site
ii. regulatory exemptions (cite exemption)	NA			NA	NA	NA
iii. approval conditions	Double liner for recirculation LFG extraction prior to recirculation			(DNREC, 2001) pp. 2 – 11	1	Based on review of permit – conditions too numerous to list
iv. reporting requirements	Annual report			(DNREC, 2001) pp. 11 – 14	1	Based on review of permit – reporting requirements too numerous to list
II. HYDRAULIC CONTAINMENT						
3. Hydrogeology						
A. Underlying geology (repeat for each layer starting with the top-most layer)	*Complete i thru iii for each layer*			(Schnabel, 1996)	1	PE-certified report (note: hydraulic conductivity values of these materials were not provided in this report)
i. materials	Miscellaneous fill – silty sand, crushed rock, and gravel.					
ii. thickness	0 to 1.5	Feet	Boring logs			
iii. characteristics	Medium density (N = 16 to 50)					
i. materials	Silty sand with gravel					
ii. thickness	25 to 38	Feet	Boring logs			
iii. characteristics	Loose to medium density (N = 4 to 32)					

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
i. materials	Elastic silt and clay					
ii. thickness	7.5 (avg.)	Feet	Boring logs			
iii. characteristics	Very soft to stiff					
Additional layers – (attach another form to continue)	Additional layers provided in report but not reproduced here.					
2. Liner Design						
A. Soil barrier layer (describe each layer)	*Complete i thru iii for each layer*			(CDM, 1999)	1	PE-signed construction certification report
i. materials	Silty sand					
ii. thickness	2	Feet	As built drawing/ description			
iii. characteristics	No information provided					
i. materials	NA					
ii. thickness	NA	NA	NA			
iii. characteristics	NA					
B. Geosynthetic layer(s) – number (describe each layer)	*Complete i and ii for each layer*					
i. materials	Geosynthetic clay liner (GCL) for Area E – Bentomat ST, re-inforced bentonite geocomposite layer on top.			(CDM, 1999)	1	PE-signed construction certification report
ii. thickness	Not specified	NA	NA	NA	NA	NA
i. materials	HDPE			(CDM, 1999)	1	PE-signed construction certification report
ii. thickness	60	Mil	As built			
C. Drainage layer(s) – number	Complete i thru iii for each layer					

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
i. materials	Washed sand			(CDM, 1999)	1	PE-signed construction certification report
ii. thickness	2	feet	As built			
iii. characteristics	Not specified			NA	NA	NA
D. Lysimeters – number	None	NA	NA	NA	NA	NA
i. type	NA			NA	NA	NA
ii. other lysimeter design information (attach drawings, as appropriate)	NA			NA	NA	NA
2. Leachate Collection and Disposal	*Complete A thru H below*					
A. Components of leachate collection	Describe each component in i thru v below					
i. piping layout/spacing (attach diagram if available)	Collection – 4-inch, SDR 17 HDPE; 0.5 –inch diameter perforations at 6 inches apart; spaced at approximately 100 feet (varies with location/depth Header – 10-inch, SDR 17 HDPE; 0.5 -inch diameter perforations at 10 inches apart Sloped south to north			(CDM, 1997a)	2	Area E and C/D Valley engineering report – no as builts
ii. material sizes/types (porous material)	Collection – washed gravel trenches wrapped with mono filament polypropylene (PP) fabric					
iii. sumps – number/design (describe each if different – attach diagrams if available)	2 – each 18-inch perforated SDR 17 HDPE risers (Area E)	NA	NA			
iv. pumps – number/design	NA	NA	NA	NA	NA	NA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
(describe each if different – attach diagrams if available)						
v. collection areas	D – 22.5 C/D – NA E – 32.5	Acres	NA	(CSWMC, 2001)	3	No basis provided; no information provided for C/D Valley
B. Collection frequency	Continuous	NA	NA	NA	NA	NA
C. Volume collected	9,424,450 2001 9,406,270 2000 8,987,405 1999 9,555,918 1998	gallons	Unknown	CD ROM	3	No basis for data provided
D. Collection rate	Not provided	Gal/ acre/ day	NA	NA	NA	NA
E. Disposal methods – sanitary, on-site treatment, recirculation, haul off-site, evaporation	Recirculation or haul off site	NA	NA	(CSWMC 2001)	3	No basis provided
F. Disposal frequency	Varies	NA	NA	NA	NA	NA
G. Disposal volumes	8,146,504 2001 8,730,047 2000 8,677,405 1999 9,256,918 1998	Gallons	Unknown	NA	3	Basis not provided
H. Disposal rates	Not provided	NA	NA	NA	NA	NA
3. Liquids Addition						
A. Liquid sources – leachate, wastewater, surface water, sludge (type and % solids), groundwater (describe – if multiples, designate each as 1, 2, 3, etc.)	Leachate			(CDM, 1997a)	2	No liquid wastes or sludges are accepted.
B. Methods of liquid addition – surficial spraying, horizontal pipes/trenches, vertical injection wells, infiltration ponds	D – vertical wells C/D Valley – subsurface horizontal injection trenches (HIT) E – HIT			(CDM, 1997a)	1	Confirmed by PE-signed construction certification report (CDM, 1999)

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
(describe)						
i. Application frequency (each source)	Varies	Times/day	NA	NA	NA	NA
ii. Application rates (each source)	14.5 gallons /100 feet of HIT length times 1.5 dosage factor (field capacity)		NA	NA	3	Operations Plan only; no supporting data provided
iii. Daily application volumes (each source)	Varies	Gallons	NA	NA	NA	NA
C.System components – general (describe and complete i thru viii below			Engineering Design	(CDM, 2002a)	2	System sketches; no true as builts or engineering certifications provided
xii. pipe sizes (list for vertical and lateral components if different)	6-inch perforated HDPE SDR 17 For lateral components, perforations are only on the top side of the pipe	NA				
xiii. pipe material	HPDE	NA				
xiv. perforation size	0.625- (diameter)	Inch				
xv. perforation frequency	3 inches apart (horizontally) 60 degrees apart (radially) – rows offset by 30 degrees	NA				
xvi. vertical spacing	20 to 25	Feet				
xvii. horizontal spacing	50 to 300	feet				
vii. backfill material/ characteristics	106 stone	NA				
viii. automation (describe; include schematics if available)	None – manual valves allow for flow control and shutoff of individual HITs	NA	Engineering Design	(CDM, 2002a)	1	Confirmed by site inspection
4. Intermediate Cover Application						

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
A. Cover layer materials (list each as 1, 2, 3, etc.)	6 inches of compacted cover (soil or shredded C&C waste) material over the daily cover	NA	Plan requirement	(CDM, 1997a) and visual observation	1	NA
i. Cover layer thickness (list for each layer in A)	6	Inches				
ii. Cover layer characteristics (describe for each)	Sandy soil or shredded C&D waste Plastic tarps					
B. Cover placement (describe areas)	The active surface area is covered by one of the following: soil, tarps, and shredded C&D waste	NA	NA	Verbal – landfill manager	1	Placement confirmed during site visit
i. vegetative growth(describe type)	NA	NA	NA	NA	NA	NA
5. Final Cover Design						
A. Gas collection or grading layer (describe and complete i thru iv)	Grading layer	NA	NA	(DNREC, 2001) pp 14 and 15	1	Requirements specified by DNREC Permit SW 97/05 issued October 24, 1997 and modified June 30, 2001; July 11, 2001; and September 20, 2001
i. number	1	Layers	NA			
ii. materials (describe each if multiple layers are present)	Sand or soil	NA	NA			
iii. thickness (for each)	6	Inches	Based on engineering design			
iv. characteristics (for each)	Not provided	NA	NA			
B. Soil barrier layer(s) - describe generally and complete i thru iv	Clay or geomembrane (see C. below)	NA	NA			
i. number	1	NA	NA			
iii. materials (list each)	Clay	NA	NA			
iii. thickness (for each layer)	6	Inches	Engineering design			
iv. characteristics (for each layer)	>1 x 10^{-7}	Cm/sec	NA			

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
C. Geosynthetic layer(s) – describe and complete i thru iii	Geomembrane underlain by geotextile	NA	NA			
i. number	1	NA	NA			
ii. materials (for each layer)	Not specified	NA	NA			
iii. thickness (for each layer)	30	Mil	Engineering design			
D. Drainage layer(s) - describe and complete i thru iv	NA	NA	NA	NA	NA	NA
i. number	NA	NA	NA	NA	NA	NA
ii. materials (for each layer)	NA	NA	NA	NA	NA	NA
iii. thickness	NA	NA	NA	NA	NA	NA
iv. characteristics	NA	NA	NA	NA	NA	NA
E. Rooting zone/vegetation layer(s)	Soil with topsoil layer on top	NA	NA	(DNREC, 2001)	1	Permit approval incorporating design standards NA
i. materials	See ii below	NA	NA			
ii. thickness	18 (soil) 6 (topsoil)	Inches Inches	Engineering design			
iii. characteristics	Not specified	NA	NA			
F. Cover placement to date – area	Not provided	NA	NA	NA	NA	NA
i. vegetative growth – type	Not provided	NA	NA	NA	NA	NA
ii. time in place	Not provided	NA	NA	NA	NA	NA
G. Components of surface water collection system – berms, piping/structures, basin	Lined swales with rip-rap barriers flow to surface water impoundments	NA	NA	Visual	1	Site inspection

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
III GAS MANAGEMENT						
1. Air Injection						
A. Methods of air injection –	No air is injected			NA	NA	NA
B. Horizontal pipes/trenches (describe and complete i thru iii; attach schematic if available)	NA			NA	NA	NA
i. number	NA	NA		NA	NA	NA
ii. design	NA			NA	NA	NA
iii. spacing/depth	NA	NA	NA	NA	NA	NA
C. Vertical injection wells (describe and complete i thru iii; attach schematic if available)	NA			NA	NA	NA
i. number	NA			NA	NA	NA
ii. design	NA			NA	NA	NA
iii. spacing	NA			NA	NA	NA
D. System components	NA			NA	NA	NA
i. pipe size and material	NA			NA	NA	NA
ii. perforation size	NA			NA	NA	NA
iii. perforation frequency	NA			NA	NA	NA
iv. vertical spacing	NA			NA	NA	NA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
v. horizontal spacing	NA			NA	NA	NA
vi. backfill materials	NA			NA	NA	NA
vii. backfill characteristics	NA			NA	NA	NA
viii. automation	NA			NA	NA	NA
E. Air application frequency	NA	NA	NA	NA	NA	NA
i. air application volumes	NA	NA	NA	NA	NA	NA
ii. air application rates	NA	NA	NA	NA	NA	NA
iii. air application strategy	NA			NA	NA	NA
2. Gas Extraction						
A. System components	4-inch PVC Schedule 80 vertical wells with perforations; combined gas and leachate collection (HIT) in C/D Valley and Area E	NA	NA	(CDM, 1997a)	2	No as builts or design certification
i. pipe size and material	4-inch HDPE connector pipes (6 for HIT) 8-inch HPE gas headers 10-inch HDPE transmission main (12 for HIT)	NA	Engineering design			
ii. perforation size	NA	NA	NA			
iii. perforation frequency	NA	NA	NA			
iv. vertical spacing	NA	NA	NA			
v. horizontal spacing	NA	NA	NA			
vi. backfill materials	1) Gravel 2) Backfill	NA	NA			

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]		UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
vii. backfill characteristics	1) #106 Stone 2) Common Borrow		NA	NA			
viii. automation	None – manual valves		NA	NA			
B. Gas extraction frequency,	Varies		NA	NA	NA	NA	NA
i. gas extraction volumes	526,300,000 531,300,000 459,800,000 528,700,000	2001 2000 1999 1998	Cubic feet	Gas meter at flare	(DSWA 2002b)	2	Could not be verified
ii. gas extraction rates	20 to 32 (range)		m^3/min	Gas meter at flare	(DSWA 2002b)	2	Could not be verified
iii. gas extraction strategy	Continuous		NA	NA	NA	NA	NA
C. Efficiency of extraction system – migration, odors, collection area/influence, areal variability	90		%	Estimate	(DSWA 2002b)	2	Could not be verified
D. Post collection uses – flare, gas-to-energy, industry	Flare (Area D is set up for collection and off-site shipment of gas		NA	NA	Visual	1	Confirmed during site visit
IV. WASTE MANAGEMENT							
1. Incoming Waste Categories and Percentages							
A. MSW breakdown	Describe and list percentages in i thru vii						
i. paper and cardboard	NA		%	NA	NA	NA	NA
ii. plastics	NA		%	NA	NA	NA	NA
iii. metal	NA		%	NA	NA	NA	NA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
iv. wood	NA	%	NA	NA	NA	NA
v. food waste	NA	%	NA	NA	NA	NA
vi. yard waste	NA	%	NA	NA	NA	NA
vii. other	NA	%	NA	NA	NA	NA
B. Industrial waste (describe)	NA	%	NA	NA	NA	NA
C. Special waste (describe)	Fly ash from General Foods – Area A/B	Unknown %	NA	Verbal	3	Could not be verified
D. Liquids (list and describe)	NA	%	NA	NA	NA	NA
E. Sludges (list and describe)	NA	%	NA	NA	NA	NA
2. Incoming Waste Processing						
A. Transfer vs. direct disposal	Unknown	NA	%	NA	NA	NA
B. Pre-placement processing						
i. shredding	No			Verbal	3	Could not be verified
ii. mixing	No			Verbal	3	Could not be verified
iii. chemical or nutrient adjustment	No			Verbal	3	Could not be verified
C. Waste placement						
i. compactive effort	Traditional compaction	NA	NA	Verbal	1	Verified during site visit
ii. size of active area	8,000 (typical)	ft^2	Estimate	Verbal	3	Could not be verified
iii. lift thickness	10	ft	Estimate	Verbal	3	Could not be verified
iv. moisture addition	Not during placement	NA	NA	Verbal	3	Could not be verified

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
3. Daily Cover Application and Odor Control						
A. Methods of daily cover – tarps, soil, foam, select waste (e.g., foundry sand), spray covers	1) Soil 2) Tarps (UV resistant) 3) Foam: 1991 – 1995 (Area D & D) 4) Shredded C&D Waste	NA	NA	(DNREC 2001) NA	1	Soil confirmed by visual observation; C&D waste stockpiled, not being shredded or used; tarps not in use. Foam machine out of service.
i. application frequency	Daily	NA	NA			
ii. application rates	NA	NA	NA			
iii. thickness	1) 6 2) NA 3) NA 4) 6	Inches NA NA Inches				
iv. removal and reuse	None	NA	NA	NA	NA	NA
B. Other odor controls – liquid additives, gas extraction, spray covers, misting systems, neutralizing vs. masking	Gas extraction	NA	NA	Verbal	1	Confirmed during site visit
4. Geotechnical Properties and Stability						
A. In-place controls – sloping, buttressing, geosynthetic reinforcement, moisture limitations	Typical liner analyses	NA	NA	NA	NA	NA
B. Field observations – sloughing, differential settlement, new waste vs. degraded waste behavior	Minor (typical) differential settlement	NA	NA	NA	NA	NA
C. Seismic considerations	Standard for Subtitle D	NA	NA	Schnabel, 1997	2	Not confirmed

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
V. LANDFILL/ BIOREACTOR OPERATION AND CONTROL						
1. Monitoring						
A. Waste solids	No	NA	NA	Verbal	NA	NA
i. sensors	NA	NA	NA	NA	NA	NA
ii. frequency	NA	NA	NA	NA	NA	NA
iii. field vs lab	NA	NA	NA	NA	NA	NA
iv. incoming vs in-place	NA	NA	NA	NA	NA	NA
v. moisture content	No (test cells only)	NA	NA	Verbal	NA	NA
vi. volatile solids	No	NA	NA	NA	NA	NA
vii. cellulose fraction	No (test cells only)	NA	NA	Verbal	NA	NA
viii. lignin fraction	No (test cells only)	NA	NA	Verbal	NA	NA
ix. pH	No	NA	NA	NA	NA	NA
x. BMP	No	NA	NA	NA	NA	NA
xi. redox	No	NA	NA	NA	NA	NA
xii. shear strength	No	NA	NA	NA	NA	NA
xiii. compressibility	No	NA	NA	NA	NA	NA
B. Waste mass - methods	No	NA	NA	NA	NA	NA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
i. sensors	NA	NA	NA	NA	NA	NA
ii. frequency	NA	NA	NA	NA	NA	NA
iii. temperature	No	NA	NA	Verbal	NA	NA
iv. settlement	A few plates	NA	NA	Verbal	NA	NA
v. in-place volume	No	NA	NA	NA	NA	NA
vi. in-place density	Yes	NA	NA	Verbal	3	No supporting data found
vii. effective density	No	NA	NA	NA	NA	NA
viii. water balance	No	NA	NA	NA	NA	NA
C. Leachate – methods	No	NA	NA	NA	NA	NA
i. sensors	NA	NA	NA	NA	NA	NA
ii. frequency	NA	NA	NA	NA	NA	NA
iii. field vs lab	NA	NA	NA	NA	NA	NA
iv. in-place vs extracted	NA	NA	NA	NA	NA	NA
v. temperature	20 to 25	^{O}C	NA	Anecdotal – monitoring supervisor	3	Massive amounts of data – not reviewed because not a major parameter for the site
vi. head	Dipstick cleanouts	inches	NA	Verbal	3	No supporting data
vii. composition	Yes	NA	NA	CD-ROM	2	Large quantity of unspecified data on CD precluded review

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
D. Liquids addition/recirculation – collection methods, frequency, field vs. lab; temperature, composition	NA	NA	NA	NA	NA	NA
E. Gas – methods, sensors, frequency, field vs. lab, in-place vs. extracted; temperature, % O_2, % CH_4, % CO_2, % N_2 or balance, VOCs, NMOCs	NA	NA	NA	NA	NA	NA
F. Surface emissions – methods, sensors, frequency, field vs. lab; temperature, % O_2, % CH_4, % CO_2, % N_2 or balance, VOCs, NMOCs	NA	NA	NA	NA	NA	NA
G Groundwater/lysimeters – methods, sensors, frequency, field vs. lab; composition	NA	NA	NA	NA	NA	NA
H. Climatologic – methods, sensors, frequency, on-site vs. off-site; temperature, barometric pressure, precipitation, wind speed, wind direction	No	NA	NA	NA	NA	NA
2. Operational Parameters or Constraints						
A. Moisture content goal or limitation	60	% (by wt)	NA	Verbal	3	Not documented
B. Temperature operating range	No	NA	NA	NA	NA	NA
3. Closure Plan						
A. Phasing – immediate placement vs. delayed	Immediate final cover placement	NA	NA	Verbal	2	Site observations supported
B. End-Use	Not identified	NA	NA	NA	NA	NA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
4. Post-Closure Maintenance						
A. Final cover maintenance – inspections, frequency, settlement problems	NA	NA	NA	NA	NA	NA
B. Environmental monitoring – groundwater, leachate, gas	NA	NA	NA	NA	NA	NA
C. Leachate collection and treatment	NA	NA	NA	NA	NA	NA
D. Gas extraction and use	NA	NA	NA	NA	NA	NA
5. Problems Encountered and Resolution						
A. Excessive Temperatures or Fire (list and describe each event; use additional paper or copy report exerpts to describe)	1 time	NA	NA	Verbal	3	No supporting documentation
B. Liquid distribution clogging (list and describe each event; use additional paper or copy report exerpts to describe)	NA	NA	NA	NA	NA	NA
C. Ponding or seeps	NA	NA	NA	NA	NA	NA
D. Leachate head > 1 ft	NA	NA	NA	NA	NA	NA
E. Odors or gas migration	NA	NA	NA	NA	NA	NA
F. Slope stability	NA	NA	NA	NA	NA	NA
G. Cover integrity	NA	NA	NA	NA	NA	NA
H. Additional costs or resources – specialized equipment, materials, or personnel	NA	NA	NA	NA	NA	NA

Landfill Characterization List – Emerald Park Site (6/24/02 – 6/26/02)

FINALIZED 12/17/03

Bioreactor Landfills – State of the Practice Analysis

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
I. GENERAL						
6. Site Conditions	Complete A thru E below					
J. Address (include both mailing address, such as a P.O. Box, and facility address if different)	W124 S10629 S.124th Street, Muskego, WI 53150					Superior Emerald Park Landfill, LLC. (SEPLI) operates a municipal solid waste landfill in the S ¼ of the NE ¼ of NE ¼ of SE ¼ of sections 36, T05N, R20E, SE ¼ of NW ¼ of section 36, T05N, R20E, Waukesha County, Wisconsin.
B. Owner (name of county or municipal government, or private firm/owner)	Onyx Waste Services/Onyx North America/Vivendi					P.O.C. is Jay Warzinzki, Regional Engineer
L. Site History	The site was originally a farm; 2 parcels were purchased in the late 1980's. SEPLI submitted a feasibility report in August 1988 and received a conditional feasibility determination in December 1992. SEPLI submitted the Plan of Operation in January 1993 and was granted a conditional approval in June 1994. Filling began in November 1994.			(WDNR, 1994) (WDNR, 2000)	1	Regulatory approval - original - expansion
M. Average disposal tonnage	2001 – 788,480.71	Tons/yr	Annual total from	(SEPLI, 2002a)	1	Confirmed by Annual

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
(annual or monthly)	2000 – 650,171.73 1999 – 746,152.40 1998 – 914,942.11		tipping records	(SEPLI, 2002b) (SEPLI, 2001a) (SEPLI, 2000a) (SEPLI, 1999)		Reports to WDNR
N. General area of refuse collection (describe the areal extent and land usage – industrial, light industrial, residential, etc.)	Southeastern Wisconsin: Milwaukee, Waukesha, Racine, Kenosha, Walworth, Ozaukee Counties			(SEPLI, 2002a)	3	Summary information from site visit; no background information provided to substantiate
F. General Climate	The average monthly temperature in ranged from 18.9 (Jan) to 70.9 °F (July), with an annual average of 46.1 °F. During the same time, the average monthly precipitation ranged from 1.45 inches (Feb) to 3.53 inches (Aug), with an annual average of 32.93 inches.			(Utah, 2002)	1	For the 30 years between 1961 and 1990; data for Milwaukee, WI.
2. Bioreactor Project Background	Complete A thru E below					
A. General layout	*Complete i thru viii below; attach site diagram, if available*					
i. area – total or cell	480 (total acreage of property) Phase 1 - 3 = 35 Phase 4 = 9.1 Phase 5 = 18.2 Phase 6 = 20.6 Total landfill area = 82.9	Acres	Design	(WDNR, 2000) (WDNR, 1994)	1	Regulatory approval of Plan of Operation
ii. volume – total or cell	Phase 1 – 3 = 3,550,360 Phase 4 = 1,679,800 Phase 5 = 1,990,400 Phase 6 = 5,970,800 Total landfill volume = 13,191,360 (to date, bioreactor Phases 1 – 4)	Yd^3	Design	(WDNR, 2000) p.8 (WDNR, 1994)	1	Regulatory approval of Plan of Operation
iii. depth – total or cell	226 (maximum) 70 feet below grade and 156 feet above grade	feet	Design	(WDNR, 2000) p.9	1	Regulatory approval of Plan of Operation

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
iv. phase	Bioreactor Phases 1 through 4 to date			(SEPLI, 2002a)	1	Confirmed by visual observation
v. module	NA			NA	NA	NA
vi. integration w/existing site	Overlay/contiguous			NA	NA	NA
vii. new cell or retrofit	New			(SEPLI, 2002a)	1	Confirmed by permit approval (WDNR, 1994) and visual observation of current activities
viii. test or full-scale	Full-scale; no control cell			(SEPLI, 2002a)	1	Confirmed by visual observation
B. Project funding	Onyx Waste Services/Onyx North America/Vivendi	NA		(SEPLI, 2002a)	3	No supporting data
C. Period of operation	Phase 1 – waste placement began 11/94 Phase 2 – waste placement began 10/96 Phase 3a – waste placement began 10/98 Leachate recirculation began 8/98 Phase 3b – waste placement began 10/99 Phase 4 – waste placement began 1/01	Yrs		(ESC, 1999)	2	Not independently verified
– full-time vs. demonstration	Pilot demonstration continued to full-time			(WDNR, 1998) (WDNR, 2000) (ESC, 1999)	1	Confirmed by visual observation
D. Primary goals and objectives	*Choose i thru vi below – describe*					
i. maximize settlement and effective density	Yes			(SEPLI, 2002a)	2	Goals not formally documented anywhere.
ii. minimize leachate disposal/treatment volume	Yes					
iii. increase gas production	Yes					
iv. reduce post-closure monitoring period	NA			NA	NA	NA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
v. beneficial reuse of liquids	NA			NA	NA	NA
vi. other (explain)	Reduce leachate contamination			(SEPLI, 2002a)	2	Not documented
E. Permit approval process	Choose i thru iv below					
i. regulatory agencies (name agencies)	State of Wisconsin, Department of Natural Resources (WDNR)			(WDNR, 2000) (WDNR, 1998)	1	NA
ii. regulatory exemptions (cite exemption)	None					
iii. approval conditions	Annual summary report on recirculation					
iv. reporting requirements	Annual summary report on recirculation					
II. HYDRAULIC CONTAINMENT						
4. Hydrogeology/Subbase	Complete A thru E below					
A. Underlying hydrogeology (repeat for each layer starting with the top-most layer)	Complete i thru iii for each layer					
i. materials	Sand and clay loams (saturated to within 5 to 10 feet of the surface – low yield; not a water source)			(WDNR, 1994)	1	Plan of Operation submitted to WDNR Top 5 feet verified with QC samples in Construction Documentation Report (Phase 4 only)
ii. thickness	140 (approximate) 75 to 125	Feet Feet	Unknown Estimated from boring logs	(RMT, 1996) (BT[2], 2001)		

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
iii. characteristics	Hydraulic conductivity ranges from 3.8×10^{-5} cm/sec to 6.4×10^{-9} cm/sec		Falling head lab hydraulic conductivity tests			
iv. seasonal high water level	805.21 (MW-115A on 4/12/01) – Phase 4 – 6 liner base elevations below historical high groundwater level	Ft MSL	Manual measurement	(SEPLI, 2002b) App. A	1	Data provide to WDNR in Annual Report
i. materials	Sand and gravel deposits and Niagara dolomite			(WDNR, 1994) (RMT, 1996) (BT[2], 2001)	2	Well logs indicate sand layers of 2 to 20 feet thick in some locations, starting at depths between 125 and 150 feet below ground surface; not present in some borings
ii. thickness	Unknown	NA	NA			
iii. characteristics	Permeability and yield not provided; local private water supply					
i. materials	Shale bedrock (Mequoketa)			(WDNR, 1994)	3	No well logs or other supporting data provided
ii. thickness	Not provided	NA	NA			
iii. characteristics	Acts as aquaclude for deeper Cambrian-Ordivician strata that serve local municipal water supplies					
2. Liner						
A. Gradient control layer						
i. materials	Sand with geotextile filter			(SEPLI, 2002a) (WDNR, 2000)	1	Regulatory document
ii. thickness	6	Inches	Design			
iii. characteristics	Not specified					
B. Soil barrier layer						

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
i. materials	Clay (onsite source)			NA	NA	NA
ii. thickness	4.0 (minimum) 4.2 (average)	Feet Feet	Comparison of survey elevations to documented subgrade survey elevations	(BT[2], 2001)	1	Construction Documentation Report (Phase 4 only)
iii. characteristics	1 x 10^{-7} (maximum) vertical hydraulic conductivity P200 > 50% Average Liquid Limit ≥ 25; minimum value = 20 Average Plasticity Index ≥ 12; minimum value = 10	Cm/sec	ASTM D5084 ASTM D422 ASTM D4318 ASTM D4318	(BT[2], 2001)	1	Construction Documentation Report (Phase 4 only)
C. Geosynthetic layer(s) – number (describe each layer)	Complete i and ii for each layer	2				
i. materials	HDPE geomembrane – textured side walls, smooth base			(SEPLI, 2002a)	1	Verified in Construction Certification (BT[2], 2001) - Phase 4 only
ii. thickness	60	Mil				
i. materials	Geotextile cushion			(SEPLI, 2002a)	1	Verified in Construction Certification (BT[2], 2001) – Phase 4 only
ii. thickness	12	Ounce/yd^2				
3. Leachate Collection Layer						
A. Drainage layer(s) – number	*Complete i thru iii for each layer*	1				
i. materials	Phases 1 to 3 – sand Phase 4 (and planned for 5 & 6) – pea gravel			(SEPLI, 2002a)	1	Verified in Construction Certification (BT[2], 2001) – Phase 4 only
ii. thickness	12 (both materials)	Inches				
iii. characteristics	> $1x10^{-2}$ cm/sec					

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
B. Lysimeters – number	None	NA		NA	NA	NA
i. type	NA			NA	NA	NA
ii. other lysimeter design information (attach drawings, as appropriate)	NA			NA	NA	NA
4. Leachate Collection and Disposal	Complete A thru H below					
A. Components of leachate collection	*Describe each component in i thru v below*					
i. piping layout/spacing (attach diagram if available)	6 LCLs in Phases 1 to 3 1 LCL in Phase 4			(SEPLI, 2002a) Figure 1	2	No additional information
ii. material sizes/types (porous material)	6-inch diameter HDPE LCP bedded in 3/8-inch to 3/4 inch washed stone					
iii. sumps – number/design (describe each if different – attach diagrams if available)	Leachate collection sumps are approximately 20 feet by 20 feet and 3 feet deep. The sumps are filled with bedding material and can hold approximately 10,000 gallons of liquid.			(SEPLI, 2002a)	2	No additional information
iv. pumps – number/design (describe each if different – attach diagrams if available)	Submersible pumps housed in 18-inch diameter SDR 9 HDPE pipes will pump the leachate. Automated transducer controls to maintain dry base (< 1-foot leachate head in base liner).			(SEPLI, 2002a)	2	No additional information
v. collection areas	Phases 1 through 4					
B. Collection frequency	Continuous drainage	NA	NA	NA	NA	NA
C. Volume collected	1994 – 212,900 1995 – 2,789,400 1996 – 1,932,900	gallons	Total volumes trucked off site and /or re-circulated	(SEPLI, 2002b)	1	2001 Annual Report to WDNR

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	1997 – 1,776,000 1998 – 4,120,148 1999 – 1,515,034 2000 – 3,095,473 2001 – 10,417,502					
D. Collection rate	Continuous	NA	NA	(SEPLI, 2002a)	2	No additional supporting data provided
E. Disposal methods – sanitary, on-site treatment, recirculation, haul off-site, evaporation	1994 to 1997 – trucked to WWTP 1998 – 77% to WWTP; 23% re-circulated 1999 to 2000 – 100% re-circulated 2001 – 92% re-circulated In the future, any excess leachate (i.e., not recycled) will be directed to a force main going directly to Milwaukee Metropolitan Sewer District (MMSD).			(SEPLI, 2002b	1	2001 Annual Report to WDNR
F. Disposal frequency	Varies	NA	NA	NA	NA	NA
G. Disposal volumes	See II.2.C and E above	NA	NA	NA	NA	NA
H. Disposal rates	26,305 - the average rate of leachate treatment /re-circulation during 2001	Gal/ calendar day	Calculated from annual totals	(SEPLI, 2002a)	1	2001 Annual Report to WDNR
5. Liquids Addition						
A. Liquid sources – leachate, wastewater, surface water, sludge (type and % solids), groundwater (describe – if multiples, designate each as 1, 2, 3, etc.)	Leachate			(SEPLI, 2002a)	1	Confirmed by visual observation
B. Methods of liquid addition – surficial spraying, horizontal pipes/trenches, vertical injection wells, infiltration ponds (describe)	Horizontal pipes/trenches			(SEPLI, 2002a)	1	Confirmed by visual observation

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
i. Application frequency (each source)	See 5.B.iii below	NA	NA	NA	NA	NA
ii. Application rates (each source)	Varies	Gal/min	NA	NA	NA	NA
iii. Daily application volumes (each source)	26,305 - 2001 average volume re-circulated	Gal/ calendar day	Unknown	(SEPLI, 2002a)	1	2001 Annual Report to WDNR
C. System components – general (describe and complete i thru viii below)	Horizontal leachate trench lined with clean stone, pipe placed then backfilled with clean stone and top is covered with 6 oz. geotextile. 100 feet of solid pipe is placed before perforated pipe. Bentonite plugs at end of each trench. Sloped at a minimum of 1%.			(SEPLI, 2002a), Figure 3	2	No as built drawings or CQA documents provided
xviii. pipe sizes (list for vertical and lateral components if different)	6 (diameter)	inches	Design			
xix. pipe material	Phases 1-3 – Sch 120 PVC Phase 4 - SDR 9 HDPE			(SEPLI, 2002a) Figure 3	2	No as built drawings or CQA documents provided
xx. perforation size	0.5 (diameter)	inches	Design	(SEPLI, 2002a) Figure 3	2	No as built drawings or CQA documents provided
xxi. perforation frequency	6	Inches	Design	(SEPLI, 2002a) Figure 3	2	No as built drawings or CQA documents provided
xxii. vertical spacing	30 to 40 (approximate) – horizontal trenches (see 5.C for details)	Feet	Design/ documentation of installation	(SEPLI, 2002b) Drawing C2	1	As-built conditions
xxiii. horizontal spacing	85 to 125 – horizontal trenches (variable depending upon depth and proximity to side wall)	Feet	Design/ documentation of installation	(SEPLI, 2002b) Drawing C1	1	As-built conditions
xxiv. backfill material/ characteristics	Clean stone and top is covered with 6 oz. Geotextile			(SEPLI, 2002a) Figure 3	2	No as built drawings or CQA documents

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
						provided
xxv. automation (describe; include schematics if available)	None			NA	NA	NA
6. Intermediate Cover Application						
A. Cover layer materials (list each as 1, 2, 3, etc.)	On-site clay soil.			(SEPLI, 2002a)	1	Verified by site observations
i. Cover layer thickness (list for each layer in A)	1	Foot	Estimate	(SEPLI, 2002a)	2	Could not be confirmed
ii. Cover layer characteristics (describe for each)	Loose clay			NA	3	Could not verify – already in place
B. Cover placement (describe areas)	Intermediate cover is temporarily used until final cover is placed, and seeded with mixture compatible to native vegetation			(SEPLI, 2002a)	1	Verified by site observation
i. vegetative growth(describe type)	See 4.B above					
7. Final Cover Design						
A. Gas collection or grading layer (describe and complete i thru iv)	6-inch minimum clay grading (intermediate cover)			(SEPLI, 2002a)	1	Verified by site observation
i. number	1					
ii. materials (describe each if multiple layers are present)	Clay grading layer					
iii. thickness (for each)	6	Inches				
iv. characteristics (for each)	Loose clay (on-site clay with same permeability range as soil barrier layer)					
B. Soil barrier layer(s) - describe generally and complete i thru iv	See i thru iv below			(SEPLI, 2002a)	2	Presence verified by site observation; details could not be confirmed

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
i. number	1					
iv. materials (list each)	Compacted select clay fill layer					
iii. thickness (for each layer)	24	Inches				
iv. characteristics (for each layer)	Maximum 1 x 10^{-7} cm/sec hydraulic conductivity					
C. Geosynthetic layer(s) – describe and complete i thru iii	Geosynthetic liner			(SEPLI, 2002a)	2	Could not be confirmed by site observations
i. number	1					
ii. materials (for each layer)	Textured, linear low-density polyethylene (LLDPE) geomembrane.					
iii. thickness (for each layer)	40	Mil	Design			
D. Drainage layer(s) - describe and complete i thru iv	Geocomposite layer			(SEPLI, 2002a)	NA	Could not be confirmed by site observations
i. number	1					
ii. materials (for each layer)	Geonet composite					
iii. thickness	NA	NA	NA			
iv. characteristics	≥ 1 x 10^{-3} cm/sec hydraulic conductivity					
E. Rooting zone/vegetation layer(s)				(SEPLI, 2002a)	2	Presence verified by site observation; details could not be confirmed
i. materials	1. General fill rooting layer 2. Topsoil layer					
ii. thickness	1. 30 2. 6	Inches Inches				

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
iii. characteristics	NA					
F. Cover placement to date – area	Final cover placement to date is Phase 1 (partial final cover placed on Phase 1 plus side slopes of Phases 2 & 3 – clay only).	NA	NA	(SEPLI, 2002a)	1	Verified by site observation – intermediate cover
i. vegetative growth – type	Temporary seeding					
ii. time in place	4 (almost) – partial cover placement on north and west slopes of Phases 1, 2, and 3 in September 1998.	years	NA	(SEPLI, 2002a)	2	Presence verified by site observation; details could not be confirmed
G. Components of surface water collection system – berms, piping/structures, basin	Diversion berms, downslope flumes, energy dissipaters, perimeter drainage ditches, sedimentation basins & biofilters.			Site observation	1	NA
III GAS MANAGEMENT						
1. Air Injection						
A. Methods of air injection –	No air injection; only extraction			NA	NA	NA
B. Horizontal pipes/trenches (describe and complete i thru iii; attach schematic if available)	NA			NA	NA	NA
i. number	NA	NA		NA	NA	NA
ii. design	NA			NA	NA	NA
iii. spacing/depth	NA	NA	NA	NA	NA	NA
C. Vertical injection wells (describe and complete i thru	NA			NA	NA	NA

PARAMETER OR MEASURMENT TYPE	**MEASUREMENT OR OBSERVATION**[1]	**UNITS**[2]	**MEASUREMENT METHOD**[3]	**DATA SOURCE**[4]	**DATA QUALITY**[5]	**COMMENTS**
iii; attach schematic if available)						
i. number	NA	NA		NA	NA	NA
ii. design	NA			NA	NA	NA
iii. spacing	NA	NA	NA	NA	NA	NA
D. System components	NA	NA	NA	NA	NA	NA
i. pipe size and material	NA	NA	NA	NA	NA	NA
ii. perforation size	NA	NA	NA	NA	NA	NA
iii. perforation frequency	NA	NA	NA	NA	NA	NA
iv. vertical spacing	NA	NA	NA	NA	NA	NA
v. horizontal spacing	NA	NA	NA	NA	NA	NA
vi. backfill materials	NA			NA	NA	NA
vii. backfill characteristics	NA			NA	NA	NA
viii. automation	NA			NA	NA	NA
E. Air application frequency	NA	NA	NA	NA	NA	NA
i. air application volumes	NA	NA	NA	NA	NA	NA
ii. air application rates	NA	NA	NA	NA	NA	NA
iii. air application strategy	NA			NA	NA	NA
2. Gas Extraction						

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
A. System components	5 existing gas extraction vertical wells, leachate collection line cleanouts & gas extraction from horizontal and leachate recirculation pipe trenches			(SEPLI, 2002a)	2	Engineering drawings provided; no as builts or CQA documentation
i. pipe size and material	6 (diameter) - vertical wells; schedule 80 PVC (See leachate section for other components)	inches	NA			
ii. perforation size	Information not provided	NA	NA	NA	NA	NA
iii. perforation frequency	Not known (in bottom 2/3 to 3/4 of the length of the open bore hole)	NA	NA	(SEPLI, 2002a)	2	Engineering drawings provided; no as builts or CQA documentation
iv. horizontal spacing (for vertical wells)	300 (approximate) – 150 foot radius	Feet	Estimate from Site Monitoring Plan	(RMT, 2001)	1	Confirmed while on site
v. spacing – horizontal trenches	85 to 125 (horizontal) 30 to 40 (approximate) (vertical)	Feet	NA	NA	NA	NA
vi. backfill materials	1 to 1.5 (vertical wells)	inch		(SEPLI, 2002a)	2	Engineering drawings provided; no as builts or CQA documentation
vii. backfill characteristics	Clean bank run gravel (no limestone) (vertical wells)					
viii. automation	NA	NA	NA	NA	NA	NA
B. Air extraction frequency	Continuous	NA	NA	(SEPLI, 2002a)	1	Verified during site visit
i. air extraction volumes	348,829,000 (2001)	Ft^3	Average gas flow (cfm) measured each month (flow meter) is multiplied times the cumulative operating	(SEPLI, 2002b) Appendix F	1	2001 Annual Report to WDNR; includes log of downtimes and reasons for downtime

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
ii. air extraction rates	29,069,083 (avg.) Air extraction rates varied from 24,416,000 (7/01) to 38,369,000 (12/01)	Ft^3/month	time (hours) metered at the fan and times 60 (minutes/hour), then rounded to the nearest 1,000 ft^3			
iii. air extraction strategy	NA			NA	NA	NA
C. Efficiency of extraction system – migration, odors, collection area/influence, areal variability	No problems reported with gas system or odors			(SEPLI, 2002a)	1	No significant odors were apparent during the site visit – the BRLF was fully operational and filling was ongoing to Phase 4.
D. Post collection uses – flare, gas-to-energy, industry	Flare			(SEPLI, 2002a)	1	Confirmed by visual observation at the site.
IV. WASTE MANAGEMENT						
1. Incoming Waste Categories and Percentages	*Describe and list percentages in i thru vii*					
A. MSW breakdown	38 – total MSW (298,074.20 tons in 2001)	%	Based on weigh tickets	(SEPLI, 2002b)	2	No supporting data provided.
i. paper and cardboard	NA	%	NA	NA	NA	NA
ii. plastics	NA	%	NA	NA	NA	NA
iii. metal	NA	%	NA	NA	NA	NA
iv. wood	NA	%	NA	NA	NA	NA
v. food waste	NA	%	NA	NA	NA	NA
vi. yard waste	NA	%	NA	NA	NA	NA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
vii. other	NA	%	NA	NA	NA	NA
B. Industrial waste (describe)	10 – foundry sand (79,594.12 tons in 2001)	%	Based on weigh tickets	(SEPLI, 2002b)	2	No supporting data provided.
C. Special waste (describe)	2001 disposal tonnage - demolition debris – 36,214.30 - C-soil, Bio – 32,096.96 - C-soil, DL * – 218,402.67 - shredder fluff – 24,094.21 - miscellaneous special waste – 100,004.25 5 4 28 3 12	% % % % %	Based on weigh tickets	(SEPLI, 2002b)	2	No supporting data provided * DL = direct landfill disposal
D. Liquids (list and describe)	None reported	%	Based on weigh tickets	(SEPLI, 2002b)	2	No supporting data provided
E. Sludges (list and describe)	None reported	%	Based on weigh tickets	(SEPLI, 2002b)	2	No supporting data provided
2. Incoming Waste Processing						

PARAMETER OR MEASURMENT TYPE	**MEASUREMENT OR OBSERVATION**[1]	**UNITS**[2]	**MEASUREMENT METHOD**[3]	**DATA SOURCE**[4]	**DATA QUALITY**[5]	**COMMENTS**
A. C&D, transfer vs. direct disposal	5 - transfer 95 – direct disposal 788,481.80 total tons of solid waste in 2001	% %	Based on weigh tickets	(SEPLI, 2002a)	2	No supporting data provided
B. Pre-placement processing						
i. shredding	None reported			NA	NA	NA
ii. mixing	None reported			NA	NA	NA
iii. chemical or nutrient adjustment	None reported			NA	NA	NA
C. Waste placement						
i. compactive effort	Two 390C Rex/CMI compactors, D8 bulldozer to spread waste on the working face	NA	NA	(SEPLI, 2002a)	2	No supporting data, but equipment observed in operation during site visit
ii. size of active area	100 to 400	Feet	Estimate			
iii. lift thickness	2	feet	Estimate			
iv. moisture addition	No surficial	NA	NA	NA	NA	NA
3. Daily Cover Application and Odor Control						
A. Methods of daily cover – tarps, soil, foam, select waste (e.g., foundry sand), spray covers	Direct and bio-treated soils Auto shredder fluff Foundry sand	NA	NA	(SEPLI, 2002a)	1	Observed during site visits – biopile and stockpile of shredder fluff
i. application frequency	Daily after close of landfill or as lift completed	NA	NA			
ii. application rates	NA	NA	NA	NA	NA	NA
iii. thickness	6 (minimum)	Inches	Estimate	Verbal	1	Observed during site visits
iv. removal and reuse	Auto fluff and soil scraped off in the			(SEPLI, 2002a)	2	Not observed

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
	morning for reuse as daily cover					
K. Other odor controls – liquid additives, gas extraction, spray covers, misting systems, neutralizing vs. masking	Gas extraction system			(SEPLI, 2002a)	1	Confirmed while on site – operations were ongoing
4. Geotechnical Properties and Stability						
A. In-place controls – sloping, buttressing, geosynthetic reinforcement, moisture limitations	Slopes (4H:1V maximum) Buttressing Moisture limitations			(SEPLI, 2002a)	2	No supporting data provided
B. Field observations – sloughing, differential settlement, new waste vs. degraded waste behavior	Differential settlement noted by operators Differences between new and degraded waste behavior also noted by operators			(SEPLI, 2002a)	2	No supporting data provided
C. Seismic considerations	None	NA	NA	NA	NA	NA
V. LANDFILL/ BIOREACTOR OPERATION AND CONTROL						
1. Monitoring						
A. Waste solids	No monitoring performed	NA	NA	NA	NA	NA
i. sensors	NA			NA	NA	NA
ii. frequency	NA	NA	NA	NA	NA	NA
iii. field vs lab	NA			NA	NA	NA
iv. incoming vs in-place	NA			NA	NA	NA
v. moisture content	NA	NA	NA	NA	NA	NA
vi. volatile solids	NA	NA	NA	NA	NA	NA
vii. cellulose fraction	NA	NA	NA	NA	NA	NA

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
viii. lignin fraction	NA	NA	NA	NA	NA	NA
ix. pH	NA	NA	NA	NA	NA	NA
x. BMP	NA	NA	NA	NA	NA	NA
xi. redox	NA	NA	NA	NA	NA	NA
xii. shear strength	NA	NA	NA	NA	NA	NA
xiii. compressibility	NA	NA	NA	NA	NA	NA
B. Waste mass - methods	NA	NA	NA	NA	NA	NA
i. sensors	NA			NA	NA	NA
ii. frequency	NA	NA	NA	NA	NA	NA
iii. temperature	NA	NA	NA	NA	NA	NA
iv. settlement	Annual	Ft - MSL	Aerial survey	(SEPLI, 2002a) Table 1	1	WDNR permit requirement
v. in-place volume	NA	NA	NA	NA	NA	NA
vi. in-place density	2,826 – 1st Qtr. 2001 2,621 – 2nd Qtr. 2001 2,933 – 3rd Qtr. 2001 2,279 – 4th Qtr 2001	Lbs/yd^3	Quarterly estimates based on tonnage placed and cubic yards consumed from ground survey	(SEPLI, 2002b)	2	NA
vii. effective density	NA	NA	NA	NA	NA	NA
viii. water balance	NA	NA	NA	NA	NA	NA
C. Leachate – methods	Weekly – volume Semi-annual – too numerous to list Annual – too numerous to list	NA	EPA and other standard methods	(SEPLI, 2002a) Table 1	1 2 1	Weekly and annual in 2001 Annual Report (SEPLI, 2002b); semi-annual not reported
i. sensors	NA			NA	NA	NA
ii. frequency	SeeV.1.C above	NA	NA	NA	NA	NA
iii. field vs lab	NA	NA	NA	NA	NA	NA
iv. in-place vs extracted	NA	NA	NA	NA	NA	NA
v. temperature	Semi-annual – 17.4	°C	Unknown	(SEPLI, 2002b)	2	Only 1 of 2 semi-annual measurements
vi. head	0.18 – LH1 0.08 to 0.43 (avg = 0.22) at LH-8 monthly	Feet	Measuring rod placed in leachate head (LH) wells 1 through 8	(SEPLI, 2002a)	1	Annual Report to WDNR; LH –2 through LH-7 dry (SEPLI, 2002b)

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
vii. composition	SeeV.1.C above	NA	NA	NA	NA	NA
viii. gradient control	0 - Phase I (not used since 1/24/97) 339,780 – Phase 2 303,120 – Phase 3 613,170 – Phase 4	Gallons	Unknown	(SEPLI, 2002b)	1	2001 Annual Report to WDNR
D. Liquids addition/recirculation – collection methods, frequency, field vs. lab; temperature, composition	Nothing beyond leachate monitoring	NA	NA	NA	NA	NA
E. Gas – methods, sensors, frequency, field vs. lab, in-place vs. extracted; temperature, % O_2, % CH_4, % CO_2, % N_2 or balance, VOCs, NMOCs	Gas probes: GMP-1 to GMP-14 – Qtrly: % CH4, % O2, air temperature, gas pressure, barometric pressure/ trends, ground conditions Gas extraction wells – Qtrly: same as probes except no gas pressure Gas lines at blower – Annual: VOCs Gas condensate – Semi-annual: same as semi-annual leachate monitoring	NA	Landtec GEM500/gauges Same TO14 NA	(SEPLI, 2002a)	1 1 1 2 2	Data provided to WDNR (SEPLI, 2002b) No data in 2001 Annual Report
F. Surface emissions – methods, sensors, frequency, field vs. lab; temperature, % O_2, % CH_4, % CO_2, % N_2 or balance, VOCs, NMOCs	NSPS Quarterly Methane (upon reaching 50 MG NMOC threshold)	ppm	Portable instrument	(RMT 1999)	NA	NA
G Groundwater/lysimeters – methods, sensors, frequency, field vs. lab; composition	Semi-annual at 30 MW and 3 PW - field: elevation, temperature, pH, conductivity - lab: ALK, hardness, COD, chloride, B, fluoride, Na, sulfate, Cd, Pb, Se, VOCs (8 Subtitle D wells only) - GW elevation only on 12 additional wells Annual - lab: VOCs	NA	NA Standard EPA Methods Standard EPA Methods	(SEPLI, 2002a)	1	Confirmed by 2001 Annual Report (SEPLI, 2002b) – App. A Note: some wells were dry and could not be sampled Original lab data sheets also included
H. Climatologic – methods,	Barometric pressure as part of gas	NA	NA	(SEPLI, 2002a)	3	Could not be verified

PARAMETER OR MEASURMENT TYPE	MEASUREMENT OR OBSERVATION[1]	UNITS[2]	MEASUREMENT METHOD[3]	DATA SOURCE[4]	DATA QUALITY[5]	COMMENTS
sensors, frequency, on-site vs. off-site; temperature, barometric pressure, precipitation, wind speed, wind direction	system; on-site personnel keep track of wind speed, temperature, and wind direction, and also have TSP monitors for air quality testing					
2. Operational Parameters or Constraints						
A. Moisture content goal or limitation	40	%	Samples from new vertical wells planned (none since re-circulation began)	(SEPLI, 2002a)	3	Goals not formally documented in writing; verbal explanation
B. Temperature operating range	<105	°F	Temperature of extracted gas	(SEPLI, 2002a)	3	Goals not formally documented in writing; verbal explanation
3. Closure Plan						
A. Phasing – immediate placement vs. delayed	Each phase is closed when it is brought to grade	NA	NA	(SEPLI, 200a)	2	No additional data provided
B. End-Use	Passive use (e.g., walking trails or green space)	NA	NA	(SEPLI, 2002a)	2	No additional data provided
4. Post-Closure Maintenance						
A. Final cover maintenance – inspections, frequency, settlement problems	Monthly – inspection Annual – surveys of settlement points 2001 annual settlement ranged from 0.45 to 1.38 (5 locations) with an average of 0.78 (project-to-date settlement is the same)	NA Ft MSL Ft MSL	Elevation surveys of settlement monitoring points	(SEPLI, 2002b) App. E	1	Elevation measurements provided in 2001 Annual Report
B. Environmental monitoring – groundwater, leachate, gas	Groundwater Leachate Gas	NA	NA	(SEPLI, 2002a)	1	Confirmed by 2001 Annual Report (SEPLI, 2002b)
C. Leachate collection and treatment	Permit requires maintenance of system for 40 years – lines cleaned annually; repairs as needed	NA	NA	(SEPLI, 2002a)	2	No additional information provided
D. Gas extraction and use	Permit requires maintenance for 40	NA	NA	(SEPLI, 2002a)	2	No additional

PARAMETER OR MEASURMENT TYPE	**MEASUREMENT OR OBSERVATION**[1]	**UNITS**[2]	**MEASUREMENT METHOD**[3]	**DATA SOURCE**[4]	**DATA QUALITY**[5]	**COMMENTS**
	years					information provided
5. Problems Encountered and Resolution						
A. Excessive Temperatures or Fire (list and describe each event; use additional paper or copy report excerpts to describe)	No problems reported	NA	NA	(SEPLI, 2002a)	NA	NA
C. Liquid distribution clogging (list and describe each event; use additional paper or copy report excerpts to describe)	None specifically noted – site expects to re-circulate saturation around horizontal lines and expects differential settlement and sacrificial lines	NA	NA	(SEPLI, 2002a)	NA	NA
C. Ponding or seeps	None noted	NA	NA	(SEPLI, 2002a)	NA	NA
D. Leachate head > 1 ft	Not observed – clean lines and check pump system	NA	NA	(SEPLI, 2002a)	2	No additional information provided
E. Odors or gas migration	No problem noted - daily cover to reduce odor - leachate system maintained Extract gas to limit subsurface migration	NA	NA	(SEPLI, 2002a)	2	No exceptional odors noted during site visits
F. Slope stability	Good condition; no problems observed	NA	NA	(SEPLI, 2002a)	2	None noted during site visit
G. Cover integrity	Good condition; no problems observed	NA	NA	(SEPLI, 2002a)	2	None noted during site visit
H. Additional costs or resources – specialized equipment, materials, or personnel	NA	NA	NA	NA	NA	NA

[1] Insert the numerical value or description for this parameter; answer "Yes" or "No" as appropriate.
[2] Supply the unit of measurement
[3] Identify the measurement method (cite ASTM, EPA, or other standardized methods); if not a measurement, describe whether the value is an estimate and how that estimate was made.
[4] Describe the source of the data (e.g., permit application, compliance report, general observation, etc.); use a summary citation format that includes the primary author or source and the date, such as "(EPA, 1998)". Record all source information (e.g., author, date, publication, volume, etc.) in the master source list and key to the summary citation.
[5] Rank the quality of the data based on the methods described in the QAPP

REFERENCES

(Norstrum 2002). Personal communications, data tables, and other information provided by Jim Norstrum of Waste Management Inc. Fall 2002.

(Simard 2002a). Information provided verbally by Andre Simard, consultant for Waste Management Inc. 2002.

(Simard 2002b).Plan sheets and report provided by Andre Simard, consultant for Waste Management Inc. 2002.

(SWANA 2002). Operation and Monitoring of a Bioreactor Landfillin Sainte Sophie, Quebec, Presented at SWANA 7th Annual Landfill Symposium, June 2002. James M. Norstrom, P.E., Engineering Director, Waste Management, Inc.; Hubert J. Bourque, P.Eng., Vice President of Landfill Operations, Intersan; and Phillip A. Smith, P.E.,
Senior Engineer – Landfill Gas, Waste Management, Inc. June 2002

[1] Insert the numerical value or description for this parameter; answer "Yes" or "No" as appropriate.
[2] Supply the unit of measurement
[3] Identify the measurement method (cite ASTM, EPA, or other standardized methods); if not a measurement, describe whether the value is an estimate and how that estimate was made.
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[5] Rank the quality of the data based on the methods described in the QAPP

REFERENCES

(Accuweather, 2002) Climatology for Nashville, TN. http://www.accuweather.com

(Caldwell & Assoc., 1992) Caldwell & Associates. Construction Plans for Williamson County Sanitary Landfill, Leachate Collection Layout. File No. 91297. November, 1992.

(CEC, 1999a) Civil & Environmental Consultants, Inc. Engineering Calculations and Supporting Materials – Bioreactor Cell Volumetric Calculations Performed by Kevin B. Wolfe, PE. April, 1999.

(CEC, 1999b) Williamson County Landfill – Topographical Map Showing Area of "Disco Area" and Sections 6 & 7. Map GID9901. February, 1999.

(CEC, 2002a) Civil & Environmental Consultants, Inc. Williamson County Aerated Bioreactor Project: Data From June 2000 to April 2002, Leipers Fork, Tennessee. CEC Project No. 200187. May 2002.

(CEC, 2000b) Civil & Environmental Consultants, Inc. Field Data Summary – Leachate Head Measurements and Calculations of Adjusted Totalized Leachate Flows For Each Area. May, 2002.

(CEC, 2002c) Field Notes for the Williamson County Aerated Bioreactor. Sampling Events Dated February, July, and November 2000; July and December, 2001; and April, 2002.

(CEC, 2002d) Civil & Environmental Consultants, Inc. Groundwater Monitoring Report: Williamson County Class I Landfill - TDSWM Permit Number SNL 94-102-0057, Franklin, Tennessee

(CEC, 2002e) Correspondence from Kevin Wolfe (CEC) dated December, 2002.

(HBA, 2002) Hall, Blake, and Associates. Solid Waste Engineering Properties - Results. May, 2002.

(NOAA, 2001) Record of Climatological Observations: Franklin Sewage Plant (Sample). http://ols.ncdc.noaa.gov/onlinestore.html

(SSS, 2000) Southern States Survey. H:\200187 - Bioreactor – Williamson County\GPS\WCLF Pyramid 1, Adjusted Coordinates. July, 2000.

(SPOT, 2002) SPOT Population Table; Williamson County. 1995 http://hitspot.utk.edu

(SSS, 2002). Southern States Survey. Williamson County Bioreactor Survey Coordinates. April, 2002.

(TDA, 2001) Tennessee Department of Agriculture, Regulatory Services, Weights and Measures Section. Scale Calibration Record Dated September 28, 2001.

(TDEC, 1995) Tennessee Department of Environment and Conservation. Letter From Robert J. McKee, Division of Solid Waste Management, Nashville Field Office, to Robert Ring, County Executive, Regarding Williamson County Class I Landfill: Construction Certification Packet for Cell 1, Area 1, SNL 94-102-0057 EXT. December 19, 1995.

(TDSWM, 2000) Tennessee Division of Solid Waste Management. Letter From Mike Apple, Director to Lewis Bumpus, Director of the Williamson County Solid Waste Management Department, Regarding Permit Modification for Cell 1: Delay in Closure Activities. January 6, 2000.

(TWI, 2000) Texas Weather Instruments, Inc. 1-Wire Station Instruction Manual/Weather View 32. May, 2000.

(Utah, 2002) www.met.utah.edu. 2002.

(Williamson County, 2002) Williamson County, TN. Material Analysis Report by Material: For the Period 10/01/1995 – 01/31/1998: Computer Inventory For Class I and Class II Wastes Received at the Bioreactor Site. May 21, 2002.

[1] Insert the numerical value or description for this parameter; answer "Yes" or "No" as appropriate.

[2] Supply the unit of measurement

[3] Identify the measurement method (cite ASTM, EPA, or other standardized methods); if not a measurement, describe whether the value is an estimate and how that estimate was made.

[4] Describe the source of the data (e.g., permit application, compliance report, general observation, etc.); use a summary citation format that includes the primary author or source and the date, such as "(EPA, 1998)". Record all source information (e.g., author, date, publication, volume, etc.) in the master source list and key to the summary citation.

[5] Rank the quality of the data based on the methods described in the QAPP

REFERENCES

Beck, 1996. R. W. Beck, Crow Wing County MMSW Landfill Permit SW-376: Cell 2 and Pond 3 Construction Documentation Report. February 1996.

Beck, 1997. R. W. Beck. Crow Wing County MMSW Landfill Permit SW-376: Cell 1 Final Cover Construction Closure Certification Report. January 1997.

Beck, 1998a. R. W. Beck, Permit Reissuance: Crow Wing County MMSW Landfill SW-376. September 1998.

Beck, 1998b. R. W. Beck. 1998 Hydrogeologic Investigation for the Crow Wing County MMSW Landfill Permit SW-376. December, 1998.

Beck, 2000a. R.W. Beck. 1999 Annual Report: Facility SW-376, Crow Wing County MMSW Landfill. January 2000.

Beck, 2001a. R. W. Beck, 2000 Annual Report: Facility SW-376, Crow Wing County MMSW Landfill. January 24, 2001.

Beck, 2001b. R. W. Beck, Cell 3 Construction Documentation Report: Crow Wing County MMSW Landfill SW-376. October 2001.

Beck, 2002a. R. W. Beck, Recirculation-to-Energy Demonstration Project Application for Crow Wing County MMSW Landfill (SW-376). March 2002.

Beck, 2002b. R. W. Beck, 2001 Annual Report: Facility SW-376, Crow Wing County MMSW Landfill. January 28, 2002.

Beck, 2002b. R. W. Beck, 2002. Summary document prepared in response to questions for this project.

Doran, 2003. Personal Conversations between Craig Benson and Fred Doran. January 2003.

MPCA, 2002a. Minnesota Pollution Control Agency, Final Draft of the Major Modifications to the Crow Wing County Wast Disposal Facility, Permit SW-376 – Incorporation of Recirculation-to-Energy Demonstration Project. August 13, 2002.

[1] Insert the numerical value or description for this parameter; answer "Yes" or "No" as appropriate.

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NOTE: Site operations personnel were unable to meet with the SAIC Team during the site visit. Specific questions could not be asked and some relevant reports may not have been provided. In addition, a massive "data dump" was provided on CD ROM for virtually every parameter monitored. This massive quantity of data could not be reviewed within the project scope.

REFERENCES

CDM 1997a. Camp Dresser and McKee. DSWA Central Solid Waste Management Center Engineering Report for the Area E and C/D Valley Disposal Areas and Related Facilities. July 1997.

CDM 1997b. Camp Dresser and McKee. DSWA Central Solid Waste Management Center Area E and C/D Valley Disposal Areas Plan of Operation. July 1997.

CDM 1999. Camp Dresser and McKee. Construction Certification Report for Area E Disposal Area - DSWA Central Solid Waste Management Center. February 1999.

CDM 2002. Camp Dresser and McKee. Operations Plan, Section 3 Leachate Recirculation System: Area E Disposal Area - DSWA Central Solid Waste Management Center. 2002.

CSWMC 2001. Central Solid Waste Management Center. Facility Fact Sheet. March 2001.

CSWMC 2002a. Central Solid Waste Management Center: "As Builts" - undated hand-sketched plan drawings 2002.

DNREC 2001. State of Delaware, Department of Natural Resources and Environmental Control, Division of Air and Waste Management. Modification of Central Solid Waste Management Center Permit SW-97/05. September 20, 2001.

DSWA 2002b Delaware Solid Waste Authority Landfill Gas Report - Central Solid Waste Management Center. January 2002.

Schnabel 1996. Schnabel Engineering Associates. Hydrogeologic and Geotechnical Investigations: Area E Landfill Expansion – Central Solid Waste Management Center, Sandtown, Delaware. October 1996.

Schnabel 1997. Schnabel Engineering Associates. Revised Calculations for Subgrade Settlement and Liner Stability: Areas C and D – Central Solid Waste Management Center, Sandtown, Delaware. July 8 1997.

www.weather.com. July 2002.

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REFERENCES

(BT^2, 2001). BT^2, Inc. Revised Construction Documentation Report – Phase 4 Liner Construction. January 2001.
(ESC, 1999). Environmental Sampling Corporation. Leachate Recirculation Assessment Report, Short-Term Trial. March 1999.
(ESC, 2001). Environmental Sampling Corporation. Letter to WDNR Re: Documentation Report, Horizontal Leachate Distribution Lines HDL – 6 & 7, Superior Emerald Park Landfill, LLC. July 31, 2001.
(MW, 2000). Montgomery Watson. Letter to WDNR Re: SEPLI Total Suspended Solids (TSP) Exceedance. December 7, 2000.
(RMT, 1996). RMT Integrated Environmental Solutions. Feasibility Report for Horizontal and Vertical Expansion, Volume 1 of 2. December 1996.

(RMT, 1998). RMT Integrated Environmental Solutions. Air Pollution Control Permit: Application for Proposed Landfill Expansion Project. November 1998.
(RMT, 1999). RMT Integrated Environmental Solutions. Transmittal Letter to WDNR of the SEPLI Surface Methane Monitoring Plan. August 23, 1999.
(RMT, 2001). RMT Site Monitoring Plan (Post Phase 4 Construction). For SEPLI 2001 Annual Report. March 2001.
(SEPLI, 1999). Superior Emerald Park Landfill, Inc. 1998 Annual Report – License No. 03290. March 15, 1999.
(SEPLI, 2000a). Superior Emerald Park Landfill, Inc. 1999 Annual Report – License No. 03290. March 15, 2000.
(SEPLI, 2000b). Superior Emerald Park Landfill, Inc. Submittal to WDNR of Revised Special Waste Management Plan and Facility Inspections. March 14, 2000.
(SEPLI, 2001a). Superior Emerald Park Landfill, Inc. 2000 Annual Report – License No. 03290. March 28, 2001.
(SEPLI, 2002a). Superior Emerald Park Landfill, Inc. Landfill Characterization List: Bioreactor Landfills – State of the Practice Analysis. July 2002.
(SEPLI, 2002b). Superior Emerald Park Landfill, Inc. 2001 Annual Report - License No. 03290. March 27, 2002.
(SEPLI, 2002c). Superior Emerald Park Landfill, Inc. Leachate Volumes Trucked to WWTP or Recirculated. July 2002.
(SEPLI, 2002d). Superior Emerald Park Landfill, Inc. Compliance Monitoring Report; Permit Number: 98SDD172; FIC Number: 268554440. March 29, 2002.
(Utah, 2002). www.met.utah.edu, 2002.
(WDNR, 1994). Wisconsin Department of Natural Resources. Plan of Operation Approval. June 3, 1994.
(WDNR, 1998). Wisconsin Department of Natural Resources. Leachate Recirculation: Short-Term Trial, Approval Letter. May 6, 1998.
(WDNR, 2000a). Wisconsin Department of Natural Resources. Plan of Operation Approval – Proposed Horizontal and Vertical Expansion: Phase 4, 5, and 6. January 14, 2000.
(WDNR, 2000b). Wisconsin Department of Natural Resources. Letter Re: TSP Air Monitoring Plan – Superior Emerald Park Landfill. March 3, 2000.
(WDNR, 2001). Wisconsin Department of Natural Resources. Phase 4 Construction Documentation Approval. January 3, 2001.