Available online at www.sciencedirect.com
ScienceDirect
Waste Management 27 (2007) 13–29
waste management
www.elsevier.com/locate/wasman

Practice review of five bioreactor/recirculation landfills

C.H. Benson [a,*], M.A. Barlaz [b,1], D.T. Lane [c,2], J.M. Rawe [d,3]

[a] *Department of Civil and Environmental Engineering, University of Wisconsin-Madison, 1415 Engineering Drive, 2214 Engineering Hall, Madison, WI 53706, USA*
[b] *Department of Civil, Construction, and Environmental Engineering, North Carolina State University, Box 7908, Raleigh, NC 27695-7908, USA*
[c] *STS Consultants, Ltd., 2821 Dairy Drive, Suite 5, Madison, WI 53718, USA*
[d] *Science Applications International Corporation, 2128 Chamber Center Drive, Ft. Mitchell, KY 41017, USA*

Accepted 13 April 2006
Available online 12 June 2006

Abstract

Five landfills were analyzed to provide a perspective of current practice and technical issues that differentiate bioreactor and recirculation landfills in North America from conventional landfills. The bioreactor and recirculation landfills were found to function in much the same manner as conventional landfills, with designs similar to established standards for waste containment facilities. Leachate generation rates, leachate depths and temperatures, and liner temperatures were similar for landfills operated in a bioreactor/recirculation or conventional mode. Gas production data indicate accelerated waste decomposition from leachate recirculation at one landfill. Ambiguities in gas production data precluded a definitive conclusion that leachate recirculation accelerated waste decomposition at the four other landfills. Analysis of leachate quality data showed that bioreactor and recirculation landfills generally produce stronger leachate than conventional landfills during the first two to three years of recirculation. Thereafter, leachate from conventional and bioreactor landfills is similar, at least in terms of conventional indicator variables (BOD, COD, pH). While the BOD and COD decreased, the pH remained around neutral and ammonia concentrations remained elevated. Settlement data collected from two of the landfills indicate that settlements are larger and occur much faster in landfills operated as bioreactors or with leachate recirculation. The analysis also indicated that more detailed data collection over longer time periods is needed to draw definitive conclusions regarding the effects of bioreactor and recirculation operations. For each of the sites in this study, some of the analyses were limited by sparseness or ambiguity in the data sets.

1. Introduction

Conventional landfills in the United States that are designed and operated in accordance with the principles described in Subtitle D of the Resource Conservation and Recovery Act (Federal Register, 1991) generally employ systems that minimize the amount of moisture entering and retained in the waste. The intent is to minimize the risk of groundwater pollution by limiting the amount of leachate and gas that is generated. This design and operation philosophy also results in decomposition of buried waste at suboptimal rates for decades if not centuries (Ham, 1993). As a result, high leachate strength 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 and barrier systems that must function for very long periods of time. This long-term requirement complicates defining a period for post-closure care (Barlaz et al., 2002), and is inconsistent with the nominal 30-yr post-closure period suggested in Subtitle D.

The level of long-term monitoring and maintenance may be reduced if the rate of decomposition is accelerated. The

* Corresponding author. Tel.: +1 608 262 7242; fax: +1 608 263 2453.
E-mail addresses: benson@engr.wisc.edu (C.H. Benson), barlaz@eos.ncsu.edu (M.A. Barlaz), lane@stsconsultants.com (D.T. Lane), rawej@fuse.net (J.M. Rawe).
[1] Tel.: +1 919 515 7676; fax: +1 919 515 7908.
[2] Tel.: +1 608 224 7267; fax: +1 608 222 3765.
[3] Tel.: +1 859 331 3678; fax: +1 859 331 3650.

0956-053X/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.wasman.2006.04.005

most common method to enhance decomposition 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, landfills that are operated to enhance waste decomposition by water addition and leachate recirculation are often referred to as "bioreactor" or "recirculation" landfills depending on the amount and type of liquid reintroduced to the waste.

Interest in the bioreactor approach was tepid initially due to concerns regarding the effectiveness of landfill lining systems and aversion to leachate production, which often resulted in groundwater contamination in unlined landfills. However, modern composite liners used for landfills limit leakage to miniscule amounts when properly installed (Foose et al., 2001; Bonaparte et al., 2002). Consequently, the introduction of water and/or the recirculation of leachate is now considered plausible and, in some cases, desirable (Pacey et al., 1999; Reinhart et al., 2002).

In addition to long-term risk reduction, there are several advantages to bioreactor landfills (Barlaz et al., 1990; Reinhart and Townsend, 1997; Pohland and Kim, 1999). Enhanced decomposition increases the rate of MSW 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 can also reduce leachate treatment costs (Pohland, 1975, 1980; Reinhart et al., 2002).

Over the last two decades there have been a variety of reports of specific aspects 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). These reports have described the potential advantages of bioreactors and have documented increases in solids decomposition and gas production at selected landfills. During the last five years, a number of full-scale bioreactor and leachate recirculation operations have been implemented in the US (Reinhart et al., 2002), in part due to greater recognition of the potential advantages of bioreactor landfills as well as more frequent regulatory acceptance. Although leachate recirculation has always been permissible under Subtitle D, many state regulatory agencies have not been receptive to bioreactor and recirculation landfills, and the addition of liquids other than leachate and gas condensate generally has not been permitted. This practice is expected to change as a result of the Research Development and Demonstration (RDD) Rule that was promulgated in March 2004 (USEPA, 2004). This rule provides state regulators with flexibility to allow landfill operators to experiment with supplemental liquid addition as long as the level of environmental protection is not adversely affected.

This paper presents an analysis of data from five full-scale North American landfills operating as bioreactors or with leachate recirculation. The objective was to provide a perspective of current aspects of practice that differentiate the operation and performance of bioreactor and recirculation landfills from conventional landfills. The study focused on liner systems, operational characteristics (leachate volumes, recirculation rates, settlements), and the impacts that bioreactor and recirculation operations have on gas generation and leachate quality. Given the relatively short time periods over which most full-scale commercial landfills have been operated as bioreactors or recirculation landfills, the study findings are limited to a current snapshot of practice and do not necessarily reflect long-term conditions.

2. Landfill characteristics

2.1. Selection

More than 100 North American landfills were initially considered as candidates for study. From this group, five landfills representative of the state of the practice were selected. Landfills were selected based on three criteria: (i) the owner was receptive and would permit public disclosure of data, (ii) operations were occurring at full-scale with the intent of enhancing decomposition (e.g., pilot studies and landfills recirculating leachate solely to eliminate or reduce leachate treatment were not included), and (iii) the collection of landfills would represent a range of conditions encountered in North America (i.e., diversity in regulations, locations, climate, waste characteristics, design, operational methods, and ownership). In addition, landfills with a longer operational period (as a bioreactor or with recirculation) and/or modern instrumentation were considered more suitable. The five landfills that were selected are summarized in Table 1. All of the landfills are located in the eastern half of North America because no western landfills meeting the selection criteria were available. Landfill Q was initially designed and operated as a bioreactor while the other landfills were all operated as a conventional landfill for some period of time prior to initiation of bioreactor or recirculation operations. Data were collected during site visits between May and September 2002.

Two notable exceptions to the selected landfills are the Yolo County Project XL Bioreactor in California and the Florida Bioreactor Demonstration Project at the New River Regional Landfill in Florida. Information on both of these landfills is being disseminated independently of this study (e.g., http://www.yolocounty.org/recycle/bioreactor.htm and www.bioreactor.org). Thus, to best use the

Table 1
General characteristics of landfills selected for study

Landfill	North American region	Owner	Average annual precipitation (mm)	Active area (ha)	Duration of leachate recirculation (yr)	Design type	Gas collection
S	Upper Midwest	Private	670	3.6	8	Recirculation with horizontal piping	Active[a]
D	East	State	1041	9.7	2	Recirculation with vertical and horizontal piping	Active
Q	Northeast	Private	940	12.1	1	Bioreactor with horizontal piping	Active
C	Upper Midwest	County	762	5.6	4	Recirculation with horizontal piping	Passive[b]
E	Upper Midwest	Private	838	17.8	4	Recirculation with horizontal piping	Active

[a] Active gas collection consisted of pumping gas from a network of wells and lines installed in the waste.
[b] Passive gas collection (Landfill C) consisted of vertical wells vented to the atmosphere.

resources allocated to this study, the Yolo County and Florida landfills were excluded.

2.2. Waste stream and filling methods

Characteristics of the waste streams and waste placement methods for each study site are summarized in Table 2. All of the landfills receive waste from a variety of sources including residential areas, light industry, and construction and demolition activities, with considerable variation of waste acceptance rates. Residential and light industrial refuse comprise the majority of the waste at each landfill, with the exception of Landfill E where these categories only comprise about 50% of the waste. Other waste types were dependent on the presence and type of local industry.

Conventional waste placement methods are being used at each of the landfills (Table 2). No effort was made at any of the landfills to process the waste (shred, mill, homogenize, etc.) prior to placement. Consequently, the waste mass at each of the landfills is highly heterogeneous. The average waste thickness varies from 20 to 34 m.

A wide variety of materials are used for daily cover (Table 2), including porous granular materials such as sand and crushed glass, fine textured soils, spray-on foams and mulches, and non-putrescible wastes (foundry sand, contaminated soils, auto shredder fluff). Two landfills actively remove daily cover prior to burial of additional waste to facilitate leachate distribution and to recover airspace.

2.3. Liner systems

Schematics of the lining used at the five landfills are shown in Fig. 1. The lining systems are typical of those required for conventional landfills by the regulatory agencies overseeing these landfills. At a minimum, each landfill has a composite liner consisting of a geomembrane overlaying either a compacted clay liner or a geosynthetic clay liner. Landfills D and Q have double liners consisting of one composite liner and one geomembrane liner, with the two liners separated by a leak detection system.

Only Landfill D was required to enhance the design of the barrier systems because the landfill was being operated as a bioreactor. Landfill D was required to use a double liner with a leak detection system. A double liner was installed at Landfill Q at the owner's discretion (a single composite liner was required), although the owner also

Table 2
Characteristics of waste stream and placement methods

Landfill	Rate of filling (Mg/yr)	Waste stream characteristics	Filling method	Daily cover	Average waste thickness (m)
S	116,000	Residential and light industrial waste, demolition waste, non-hazardous industrial waste	Conventional filling with heavy compactor in 3 m lifts	Sand and crushed glass ∼150–300 mm thick, tarps. Removed and reused daily	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). No removal	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, and shredded paper). No removal	20
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	34

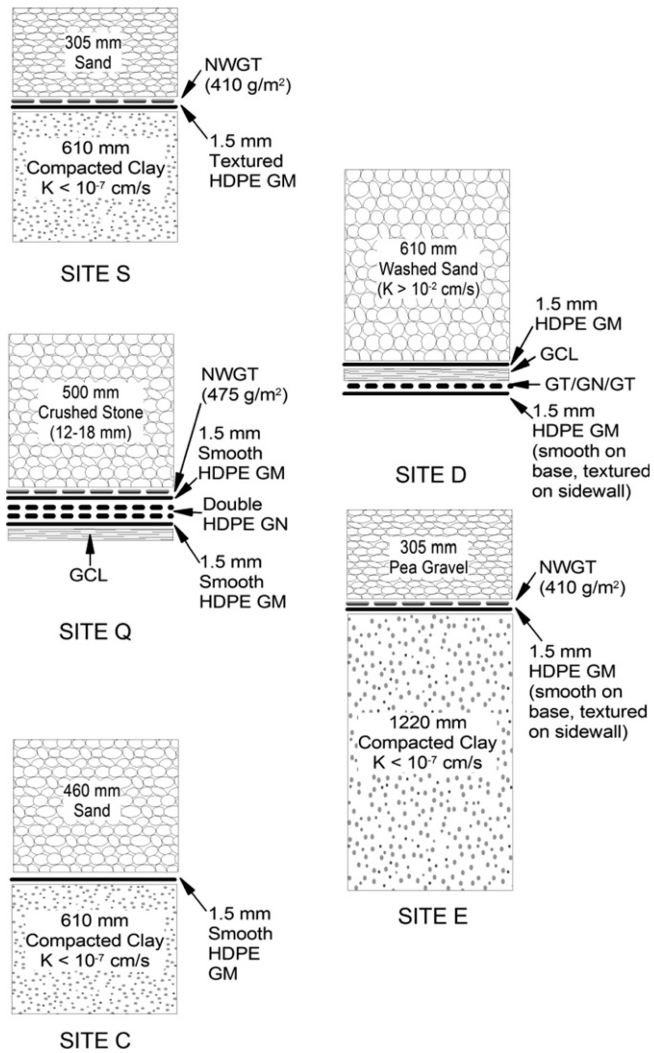

Fig. 1. Schematic profiles of lining systems. NWGT = non-woven geotextile, GM = geomembrane, GN = geonet, GT/GN/GT = geocomposite of geonet with geotextiles bonded to each side, GCL = geosynthetic clay liner, HDPE = high density polyethylene, K = saturated hydraulic conductivity.

indicated that installation of a double liner facilitated approval of the permit to operate as a bioreactor.

2.4. Leachate collection and recirculation systems

Characteristics of the leachate collection systems (LCSs) are illustrated in Fig. 1. Crushed stone or pea gravel is used as the primary component of the LCS at Landfills E and Q to promote rapid flow of leachate and to reduce the potential for fouling. Medium sand is used for the LCS at the other three landfills (C, S and D), although the leachate collection lines at these landfills are bedded in gravel. None of the leachate collection layers had additional regulatory requirements beyond those for conventional landfills. The leachate collection lines used at each landfill are typical of those used at conventional landfills (e.g., perforated 150-mm HDPE pipe).

A summary of characteristics of the recirculation systems is shown in Table 3. Leachate or contaminated runoff is the only liquid being recirculated. Horizontal distribution lines buried in trenches filled with gravel or tire chips are the most common method for leachate distribution, although leachate is distributed by spray application on the working face and top deck at one site. The distribution lines typically are perforated pipe, 100–150 mm in diameter and 10–30 m long, and spaced 18–60 m horizontally and 6–11 m vertically.

Vertical injection lines and infiltration galleries have been tried at Landfills S and D. Unconfirmed operations reports by most of the owners of these five landfills indicated that vertical injection lines and infiltration galleries are less effective than horizontal distribution lines, and vertical injection tends to cause leachate to short circuit directly to the LCS. Consequently, Landfill S has discontinued vertical injection, and Landfill D only uses vertical injection lines and infiltration galleries in older cells.

2.5. Gas control systems

Characteristics of the gas collection systems are summarized in Table 4. Four of the landfills (D, E, Q, and S) are operating active gas collection systems with flares (i.e., collection systems where gas is removed by pumping from a network of wells and pipes installed in the waste). Landfill C uses a passive system consisting of vertical wells vented to the atmosphere (i.e., gas escapes due to natural pressure gradients). At the landfills with active gas systems, gas collection generally is suspended in areas where the waste is being dosed with leachate because introduction of leachate can temporarily block gas collection lines.

2.6. Monitoring programs

Monitoring programs used at each landfill are summarized in Table 5. All of the landfills include conventional monitoring systems required for regulatory compliance. The leachate and groundwater monitoring programs include analyses for inorganic and organic contaminants along with indicator variables at prescribed intervals. Gas monitoring generally consists of flow rate (when there is an active gas collection system), percentage CH_4 and CO_2, and periodic measurement of concentrations of volatile organic compounds (VOCs). Surveys of surface emissions of VOCs have been conducted at Landfill C, which has a passive gas collection system.

Landfill Q, which is interested in optimally degrading and stabilizing waste, was the only landfill with an extensive monitoring system installed specifically for bioreactor operations. This monitoring system included in situ measurements of water content, temperature, and pressure combined with settlement measurements and periodic solids sampling. Relatively simple systems (e.g., settlement plates and/or aerial surveys, periodic leachate monitoring) are being used at the other landfills where recirculation is

Table 3
Summary of characteristics of leachate recirculation/injection systems

Landfill	Conveyance	Injection method	Application frequency	Automation
S	Trucked from storage tank to distribution lines. Leachate discharged by gravity to the recirculation line	Horizontal lines at two elevations in 0.6 × 0.6 m trenches backfilled with washed stone (22–38 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	None
D	Leachate pumped to horizontal trenches via force main	Horizontal lines in stone (38–64 mm)-filled trenches (0.6 m × 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	Could not be determined	Distribution to lines is manually switched
Q	Liquid pumped from sumps into a header surrounding the bioreactor cell and distributed to recirculation trenches	Horizontal lines in 1.0 × 1.0 m trench backfilled with crushed stone (12–18 mm). Spaced 6 m vertically and 20 m horizontally. Pipe is HDPE 75 mm in diameter with 13 mm perforations spaced at 100 mm	Continuous. Lines dosed sequentially, with each line being dosed approximately every 10 days	Leachate collection and recirculation operates continuously in response to leachate level in sump. Distribution to trenches is controlled manually using valves
C	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 × 0.6 m trench filled with 150 mm tire chips	Dose lines sequentially, with ≈1–2 days per line to achieve target dose of 290 L/m	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	Pumped via force main to horizontal distribution lines	Horizontal lines spaced at ∼11 m vertical and 32 m horizontal (average) and sloped ⩾1%. 150 mm SDR 9 HDPE pipe with 12 mm perforations spaced at 150 mm. Trench is filled with clean stone (38 mm) and covered with non-woven geotextile (200 g/m^2). 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	Leachate recirculation pump controller at leachate lift station. Manual valves for injection to distribution lines

NWGT = non-woven geotextile.

practiced to enhance (but not necessarily optimize) biodegradation and settlement is the primary goal.

None of the landfills include automated settlement measurements and all of the point measurements are made using conventional land surveying methods. Density is estimated at all of the landfills based on mass landfilled and the volume consumed, and periodically by bucket augering at two landfills (S and Q). In situ monitoring of water content is conducted only at Landfill Q, but the water content data were not made available for this study. Leachate temperatures are monitored at two of the landfills (S and Q) and liner temperatures are measured only at Landfill Q. No special monitoring was required for any of the landfills by their regulatory agencies.

3. Leachate management

3.1. Leachate treatment and recirculation volumes

Average annual leachate volumes being managed at each landfill are summarized in Table 6. In Table 6, the volume of leachate recirculated refers to the actual

Table 4
Summary of characteristics of gas collection systems

Landfill	Method	Collector	Operation frequency	Metering
S	Active	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	Total extraction rate measured at flare, and metered at each well head
D	Active	Vertical gas wells and horizontal recirculation lines	Continuous, except horizontal recirculation lines shut off during dosing	Total extraction rate measured at flare
Q	Active	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, except when leachate recirculated in adjacent lines	Total extraction rate measured at flare
C	Passive	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 wide, 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	Point measurements made annually with hot wire anemometer
E	Active	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 2/3 to 3/4 of depth of waste	Continuous	Total extraction rate measured at flare

volume of liquid returned to the waste, whereas the volume of leachate generated refers to leachate collected from LCSs at the landfill (some of which are in non-recirculation cells) as well as contaminated runoff (when data were available).

Landfill C has been treating more than half of the leachate collected annually using on-site pretreatment ponds, largely because cold weather at this landfill precludes recirculation during the winter. Treated leachate is spray-applied to the surface of an adjacent closed landfill when recirculation is not possible. The recirculation system at Landfill C was recently upgraded with an insulated and heated pipe network to prevent freezing, which will permit year-round recirculation. Thus, the fraction of leachate treated at Landfill C should decrease to near zero. The fraction of leachate recirculated is lower at Landfill D because of regulatory issues. Recirculation has been prohibited in older cells at Landfill D that have less sophisticated liners and the owner is not yet prepared to recirculate all of the leachate in the newest cell where recirculation is still permitted.

3.2. Leachate generation rate

An evaluation was conducted for Landfills Q and C to determine how leachate recirculation has affected the leachate generation rate. These landfills were selected because leachate volumes were recorded regularly while the landfill operated conventionally and then as a bioreactor or recirculation landfill. Leachate generation rates for Landfills Q and C are presented in Figs. 2 and 3, respectively. The slopes of the cumulative leachate generation curves for Landfill Q (Fig. 2) appear to be unaffected by the onset of recirculation. At Landfill C, the leachate generation rate has decreased since recirculation began (Fig. 3).

Landfill S has adjacent conventional and bioreactor cells (three subcells each) of nearly identical size and geometry that have been operated under nearly identical conditions (except for recirculation of leachate) over the same period. Leachate generation rates for Landfill S are summarized as box plots in Fig. 4. The leachate generation rates from the bioreactor landfill are slightly lower than those from the

Table 5
Summary of monitoring programs

Landfill	Waste physical properties	Chemical/ biological properties	Leachate	Gas	Surface emissions
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
D	In place density computed based on mass landfilled and volume consumed via ground survey	None	Temperature, pH, electrical conductivity, and depth weekly in sump. Flow measured based on pump rate from sump. Index variables monthly at sump and metals at collection tank	Monthly flow, CH_4, and balance gases measured at flare. O_2, vacuum, temp. measured at well heads	Surface monitoring for CH_4 at 10 locations across cover
Q	Settlements measured using settlement plates buried in 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 landfilled and volume consumed	Lignin, cellulose, hemi-cellulose	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 at each extraction line	None
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 × 30 m grid
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 CH_4 and O_2, temp.; VOCs annually in gas system and gas probes outside waste	Quarterly methane scan per NSPS requirements

Table 6
Typical leachate generation and recirculation rates

Landfill	Typical leachate volume generated		Typical leachate volume recirculated		% Leachate not recirculated
	(L/yr)	L/m^2	(L/yr)	L/m^2	
S	3,020,600	84	3,020,600	84	0
D	5,400,900	56	2,008,000	21	63
Q	19,771,000	163	19,771,000	163	0
C	8,020,100	143	3,380,600	60	58
E	18,962,400	106	17,932,500	100	5

conventional landfill, even though the leachate pumped from both landfills is recirculated into the bioreactor landfill along with contaminated surface runoff.

The data in Figs. 2–4 suggest that, at least in the short term, leachate generation rates from the bioreactor and recirculation landfills are not dramatically different from those from conventional landfills. The most likely explanation for this observation is that the waste is below field capacity and is continuing to absorb the recirculated leachate. However, seasonal and annual variations in climate can greatly affect leachate generation rates, and may mask any change in leachate generate rate due to recirculation. For example, a rise in the leachate generation rate for Landfill C is evident for 2001 (Fig. 3), but the cause of this rise,

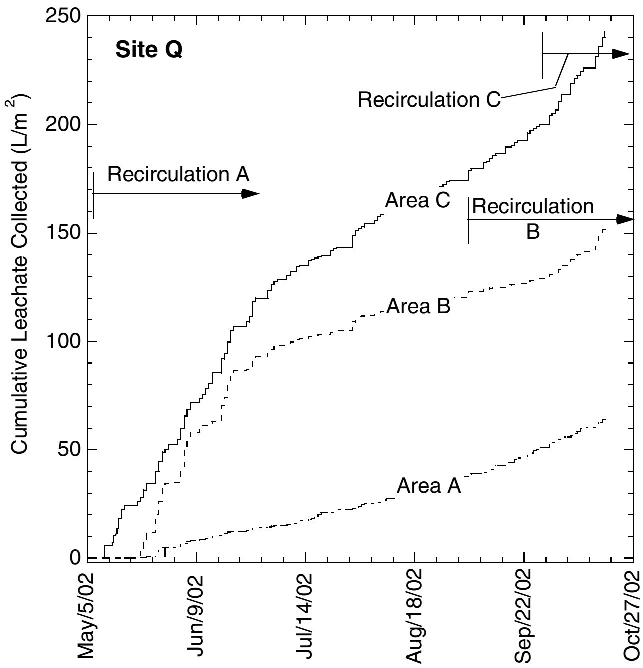

Fig. 2. Cumulative leachate collected per unit area at Landfill Q before and after recirculation was initiated.

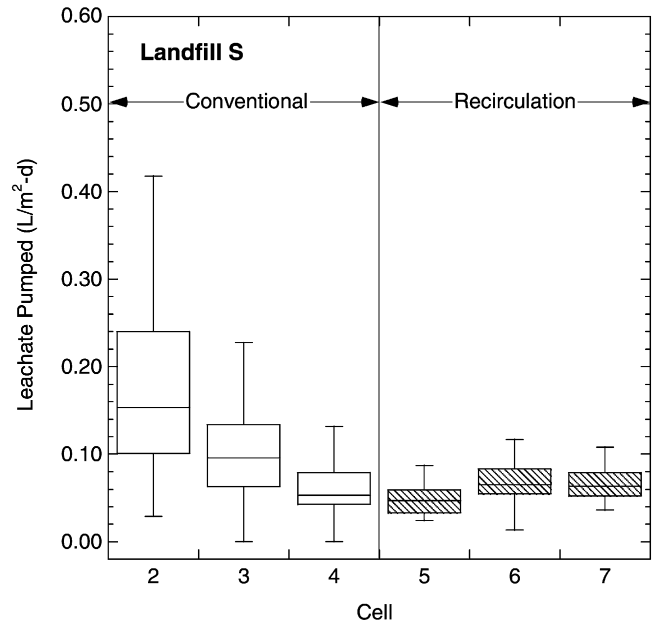

Fig. 4. Box plots showing leachate volume pumped per unit area in the conventional and recirculation cells at Landfill S. Each cell contains three subcells (2–4 in conventional landfill, 5–7 in recirculation landfill), each with a separate sump. The central line in the box represents the median and the outer boundaries of the box represent the inter-quartile range (25th–75th percentiles). The lines extending from the upper and lower sides of the box constitute the 5th and 95th percentiles of the data.

and whether the rise represents a trend, is unclear. This rise could be due to recirculation or additional precipitation, both of which are higher during the last year of record.

3.3. Leachate application frequency, dosages, and cumulative recirculation

The application frequency, recirculation dosage, and cumulative recirculation at each landfill are tabulated in Table 7. Most of the landfills dose each leachate distribution line every 10–14 days. The application frequency depends on the availability of leachate and the level of automation (Table 3), with more regular dosing at landfills with some automation (C, E, Q). Factors such as availability of leachate and weather conditions also affect the frequency of dosing (e.g., trucking leachate to the recirculation pipes at Landfill S is impractical during wet weather).

The dosage varies considerably among the landfills, with the average dosage ranging from 2.7 to 870 L/m-pipe. The dosage at a given landfill may vary by more than an order

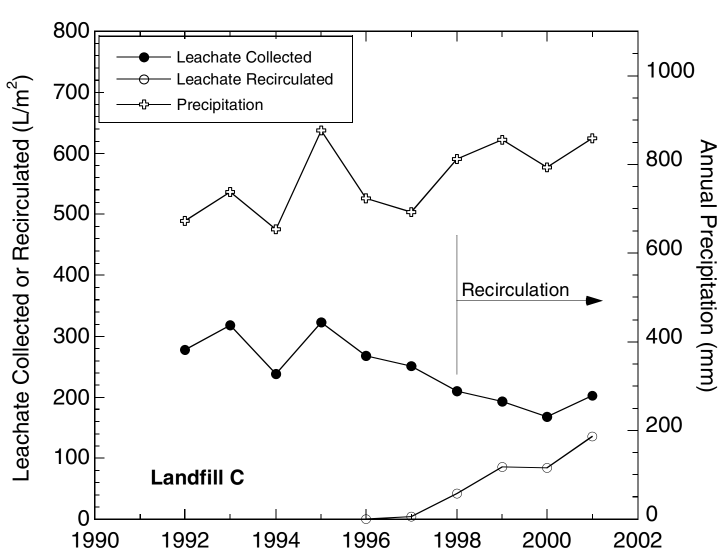

Fig. 3. Annual leachate collected and recirculated along with annual precipitation at Landfill C between 1992 and 2001.

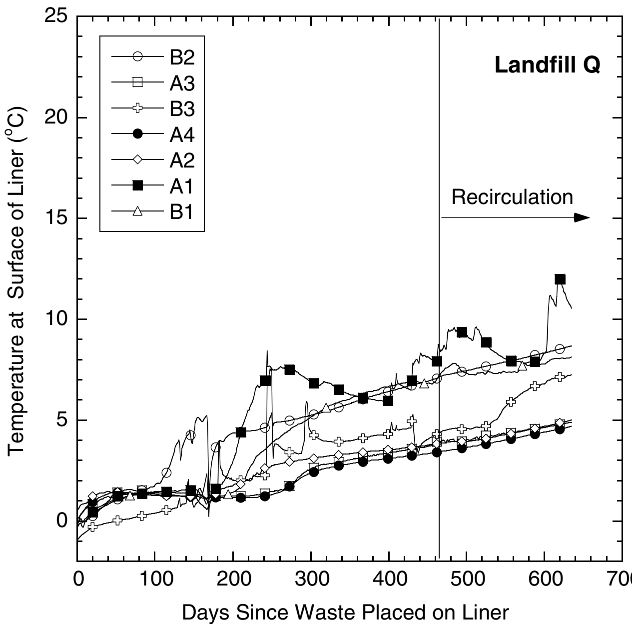

Fig. 5. Temperatures measured at seven locations on the surface of the liner for Landfill Q. Data collection began shortly after the cell began filling. Recirculation began 465 days after data collection began.

of magnitude over time. The typical dosage depends more on the operational philosophy of the landfill than on the volume of waste dosed by each recirculation line. Higher dosages are used at Landfill Q, which is trying to optimize waste degradation, whereas lower dosages are used at landfills that are recirculating with the intention of diverting leachate while concurrently enhancing waste degradation (S, D, C, E).

Cumulative recirculation (i.e., total amount of leachate recirculated per mass of waste) is also summarized in Table 7. The cumulative recirculation falls into two groups, 16.0–29.2 L/Mg-waste and 419 L/Mg-waste. The relatively low rate of recirculation for most of the landfills may reflect the regulatory prohibition on supplemental liquid addition at the time of this study. The range of recirculation rates illustrates the potential opportunity for increased recirculation by supplemental liquid addition. As was found for the dosage, higher cumulative recirculation has occurred at Landfill Q, which intends to optimize waste degradation. The potential change in moisture content can be inferred from the cumulative recirculation if all of the liquid recirculated into the waste is assumed to be uniformly distributed and fully retained. Assuming waste at an initial moisture content of 15%, the low and high ranges of cumulative recirculation correspond to cumulative increases in moisture content (wet weight basis) of less than 1%, and 16–25%, respectively. Increasing the moisture content from 15% to 45% (a typical field capacity) requires approximately 550 L/Mg-waste. Thus, in the absence of supplemental liquid addition, reaching field capacity may take considerable time at the recirculation rates currently being used at four of the landfills.

3.4. Leachate depths and liner/leachate temperatures

A concern regarding bioreactor operations is that reintroduction of leachate may raise the depth of leachate in the leachate collection layer, increasing potential leakage to groundwater. A second concern is that exothermic reactions associated with waste degradation may cause temperatures to increase and damage lining system components as well as leachate and gas management appurtenances. Leachate depth and temperatures were evaluated using data from Landfills C, Q, and S, where comparisons could be made between conventional and bioreactor conditions.

Average monthly leachate temperatures measured in the sumps of the conventional and bioreactor cells at Landfill S during 2002 varied within the same narrow range (10–13 °C) over the entire year. In addition, leachate temperatures in the conventional and bioreactor landfills never varied from each other by more than 2 °C (Benson et al., 2003). Temperatures at the surface of the liner at Landfill Q are shown in Fig. 5. Low temperatures exist at the onset of monitoring because filling commenced towards the end of winter. The temperatures then gradually increase as the liner, insulated with waste, warms in response to heat flow from the underlying earth and the overlying waste. The gradual increase in temperature exists throughout the data record, with no apparent effect attributable to recirculation.

Weekly average leachate depths during 2002 in the conventional and bioreactor landfills at Landfill S are shown in Fig. 6. Comparable leachate depths were recorded in both landfills, with those in the 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 Landfill Q are shown in Fig. 7. There are a few points in the record before and after recirculation began when the

Table 7
Cumulative recirculation, application frequency, and dosage

Landfill	Total recirculation (L/Mg waste)	Application frequency	Dosage (L/m-pipe)		
			Typical	Maximum	Minimum
S	16.0	≈10–14 days	434	744	124
D	16.9	Varies	2.7	–	–
Q	419	≈10 days	870	3995	30
C	29.2	≈10–14 days	280	474	146
E	19.1	Varies	–	–	–

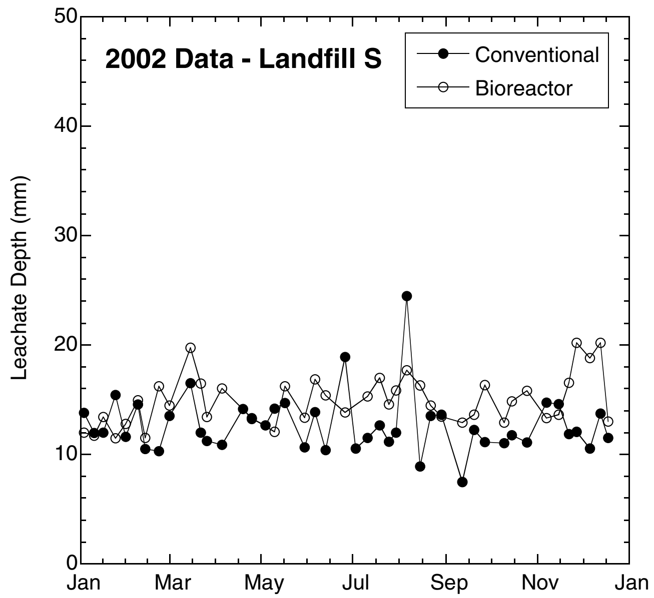

Fig. 6. Weekly average leachate depths in conventional and bioreactor landfills at Landfill S.

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 depths at Landfill Q have remained low (typically less than 50 mm) during conventional and bioreactor operations.

Leachate depths are also being recorded at Landfill C monthly. Depths no greater than 13 mm have been recorded, regardless of whether the landfill was operating conventionally or as a bioreactor, and there is no trend in the data over time (Benson et al., 2003).

4. Waste decomposition

4.1. Gas production

Gas data were evaluated to determine if greater gas production could be detected from the bioreactor or recirculation operations. The CH_4 production rate (G) usually is described by the first order rate equation (USEPA, 1998):

$$G = WL_0ke^{-kt} \tag{1}$$

where W is the annual waste mass acceptance rate, L_0 is the ultimate CH_4 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 recommended in AP-42, USEPA, 1995) and 0.05 yr^{-1} (as recommended in the New Source Performance Standards, USEPA, 1999), both of which were developed for conventional landfills. This rate is approximately a factor of two lower than is commonly assumed in Europe (Coops et al., 1995), but is commonly accepted in the US for prediction of gas production. If decomposition is occurring at a higher rate than expected for a conventional landfill (i.e., as anticipated in a bioreactor or recirculation landfill), then the CH_4 production rate predicted by Eq. (1) should be larger than that based on $k = 0.04–0.05\ yr^{-1}$. Accordingly, Eq. (1) was used to determine if the gas data collected in this study indicated that bioreactor operations were resulting in enhanced decomposition rates (i.e., rates higher than predicted with Eq. (1) using $k = 0.04–0.05\ yr^{-1}$). Sufficient data for such an analysis were available for Landfills S, D, Q, and E.

Methane production for Landfill E for 1999–2001 is summarized in Table 8 along with predictions made with Eq. (1) using a decay rate of 0.05 yr^{-1}. The ultimate meth-

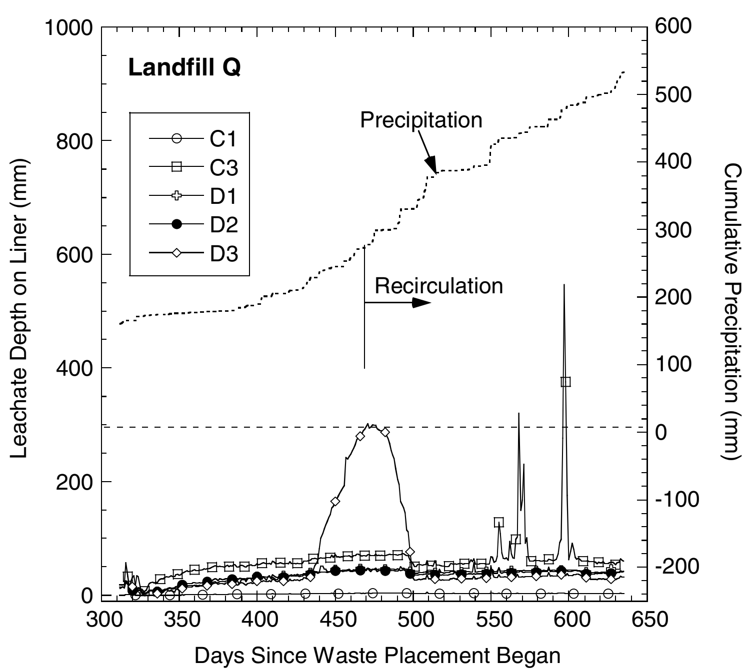

Fig. 7. Leachate depth on the liner at five locations at Landfill Q. The horizontal dashed line corresponds to the common maximum leachate depth in North America (300 mm).

Table 8
Measured and predicted methane production rates for Landfill E

Year	Measured methane production (m^3CH_4/yr-Mg waste)	Predicted methane production (m^3CH_4/yr)			
		$L_0 = 170$ (m^3/Mg)	$L_0 = 100$ (m^3/Mg)	$L_0 = 54$ (m^3/Mg)	$L_0 = 38$ (m^3/Mg)
2001	8.0	21.4 (0.38)	12.6 (0.64)	6.80 (1.19)	4.80 (1.69)
2000	9.7	18.1 (0.53)	10.7 (0.91)	5.8 (1.68)	4.0 (2.38)
1999	7.3	19.7 (0.37)	11.6 (0.64)	6.2 (1.18)	4.4 (1.67)

Number in parentheses is ratio of measured to predicted methane production.

ane yield (L_0) was set at 170 m^3/Mg (assumed by the landfill owner when making calculations), 100 m^3/Mg (recommended in AP-42), or 38–54 m^3/Mg. The latter two values were computed assuming 100 m^3/Mg as recommended in AP-42 and considering that 46–62% of the waste received at the landfill had low CH_4 potential (foundry sand, contaminated soil, construction and demolition debris, etc.).

The predicted CH_4 production varies considerably depending on the magnitude of L_0. Regardless, the measured CH_4 production only exceeds that predicted for conventional landfill operations for $L_0 = 38$ or 54 m^3/Mg. However, this comparison does not demonstrate that bioreactor operations at Landfill E have not altered the rate of gas production. For example, the efficiency of landfill gas collection was likely less than 100% because gas was not being collected from the entire landfill and only a small portion of final cover had been placed. Given the uncertainties in waste composition and gas collection system efficiency, definitive conclusions regarding the effect of bioreactor operations on gas production cannot be drawn for Landfill E.

Gas production rates for the conventional and bioreactor cells at Landfill S are presented in Fig. 8. The mean CH_4 concentrations for the conventional and bioreactor cells are 49% and 50%, respectively, meaning that the gas flow rates can be compared to assess CH_4 production rates. If the gas collection systems in the control and bioreactor cells are assumed to be equally efficient, then the data in Fig. 8 suggest that the bioreactor landfill is producing 14% more CH_4, on average, than the conventional landfill. However, the assumption of equal efficiency may not be correct because vertical gas wells, as well as recirculation lines, are being used for gas collection in the bioreactor landfill, and the total screened length of vertical wells in the bioreactor landfill is greater than that in the conventional landfill, potentially resulting in more complete gas collection. 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 (Fig. 9). When normalized per unit length of well screen, the gas flow rate for the bioreactor cell is 69% higher than that for the conventional cell. A two-tailed test confirmed that the difference in these mean flow rates is significant at the 5% level ($p = 0.0003$).

Predictions of gas production at Landfill S were made with Eq. (1) assuming that the mass of waste in the bioreactor landfill was buried in equal quantities over 6 years (87,000 Mg/yr, based on landfill records), $L_0 = 100$ m^3/Mg, and that the gas collection systems were completely

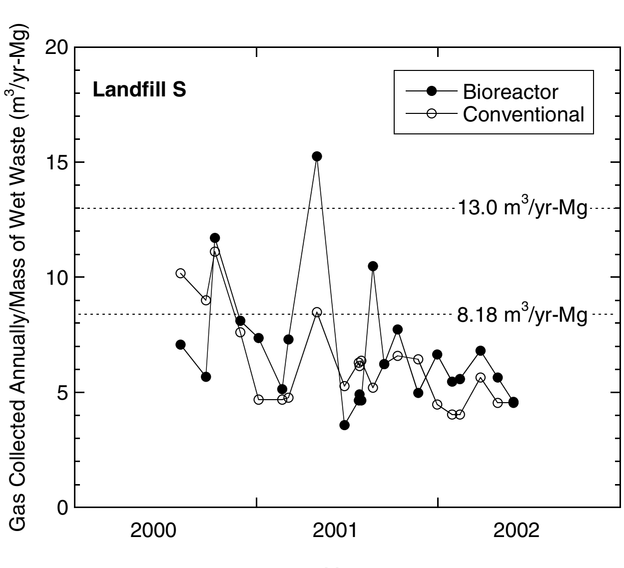

Fig. 8. Gas collected from conventional and bioreactor landfills at Landfill S per unit mass of waste.

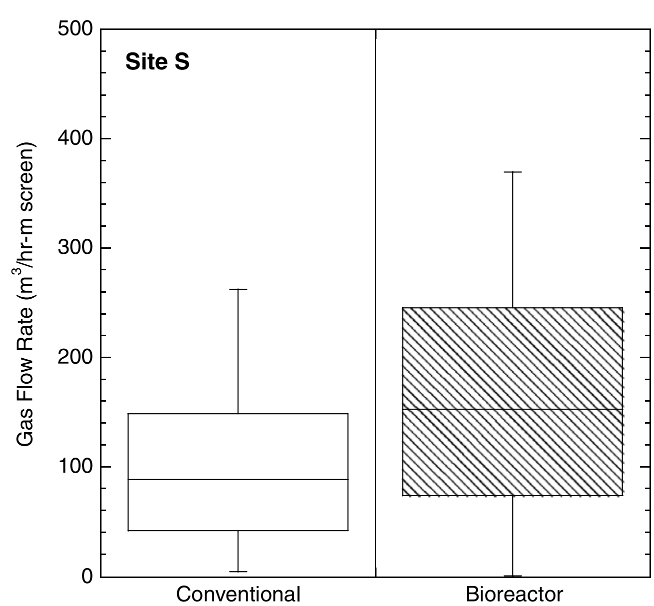

Fig. 9. Box plots showing gas flow rates per unit length of well screen from conventional and bioreactor landfills at Landfill S.

Table 9
Summary of predicted and measured methane production rates for Landfill D

Year	Predicted methane emission (kg-CH_4 per Mg-waste)	Measured methane emission (kg-CH_4 per Mg-waste)	Measured/predicted
1997	2.7	2.8	1.03
1998	2.8	2.5	0.90
1999	2.9	2.2	0.77
2000	3.1	2.9	0.94
2001	3.2	2.9	0.90

efficient. Calculations were made for $k = 0.05$ and $0.1\ yr^{-1}$. For a 7-yr period, these calculations yielded a gas production rate of $8.18\ m^3$ CH_4/Mg-yr for $k = 0.05\ yr^{-1}$ and $13.0\ m^3$ CH_4/Mg-yr for $k = 0.1\ yr^{-1}$, both of which are higher than the measured gas production rate (Fig. 8). Thus, although the measured gas production is higher in the bioreactor cell, the data do not support $k > 0.05\ yr^{-1}$.

The bioreactor cell at Landfill S probably is producing less gas than predicted by Eq. (1) because the total volume of leachate recirculated at the time of this analysis was less than that theoretically required to increase the water content of the waste by 1%. Also, no allowance was made for uncollected gas or for the fraction of non-degradable waste in the calculations. However, even if 25% of the waste was assumed to have low CH_4 potential (which is an upper bound for the waste stream at Landfill S), the CH_4 production rate from the bioreactor cell still would not support k much in excess of $0.05\ yr^{-1}$.

The analysis for Landfill D was limited to those portions of the landfill where recirculation had been conducted for the longest period. Measured and predicted CH_4 production rates for Landfill D are summarized in Table 9. The predictions were made assuming $L_0 = 100\ m^3/Mg$ and $k = 0.05\ yr^{-1}$. The measured and predicted CH_4 production rates are comparable for most years, except 1999. Thus, the data from Landfill D do not support a higher decay rate than is normally assumed for conventional landfills. This finding does not necessarily indicate that decomposition has not been accelerated at Landfill D; only that the gas production data are insufficient to confirm that decomposition is occurring at an accelerated rate.

A comparison of gas production rates for Landfill Q is summarized in Table 10. 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 Eq. (1). In all cases, the CH_4 concentration was set at 46% (the average CH_4 content measured on site, Benson et al., 2003). In Cases I–III, 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 set at $0.1\ yr^{-1}$ for waste subject to recirculation (or $0.15\ yr^{-1}$ for case III) and $0.05\ yr^{-1}$ for waste not subject to recirculation. The ultimate yield (L_0) was set at $50\ m^3$/Mg, based on the composition of the waste at the landfill, or $100\ m^3$/Mg (AP-42 recommendation).

For $L_0 = 50\ m^3/Mg$, the predicted gas production rate is 26–68% of the measured gas production rate. For $L_0 = 100\ m^3/Mg$, the predicted gas production rate is 53–135% of the measured gas production rate, with the larger percentages associated with higher decay rates. More importantly, the measured and predicted gas production rates are comparable only for $k > 0.05\ yr^{-1}$, regardless of the ultimate yield that was assumed. Thus, at Landfill Q, the gas recovery data support accelerated decomposition. In addition, Landfill Q was the only landfill initially designed and operated as a bioreactor.

4.2. Solids

At the time of this study, reliable solids analyses had only been conducted at Landfill S. These analyses were conducted on samples collected from the conventional and bioreactor cells by drilling through the waste using a bucket auger. The average volatile solids content was 54% in the conventional landfill and 31% in the recirculation landfill, suggesting that additional decomposition had occurred in the bioreactor cell (Goldsmith and Baker, 2000). This finding is consistent with data regarding solids decomposition in other bioreactor studies (Townsend et al., 1996; Mehta et al., 2002).

5. Leachate quality

Leachate quality was examined for all landfills except Q, for which insufficient data were available. Landfills C, D, and E provide a perspective on how leachate quality changes as a result of bioreactor/recirculation operations

Table 10
Predicted gas production at Landfill Q calculated with Eq. (1) for 2 years since burial of waste

Case	Decay rate (yr^{-1})	Status of waste	Mass producing methane (Mg)	Predicted gas production rate (m^3/Mg-yr)	
				$L_0 = 50\ m^3/Mg$	$L_0 = 100\ m^3/Mg$
I	0.05	Recirculation	657,000	4.2	8.5
II	0.10	Recirculation	657,000	7.9	15.8
III	0.15	Recirculation	657,000	11.0	22.1
IV	0.10	Recirculation	657,000	6.4	12.9
	0.05	No recirculation	443,000		

The average methane production rate is $16.1\ m^3$/Mg-yr.

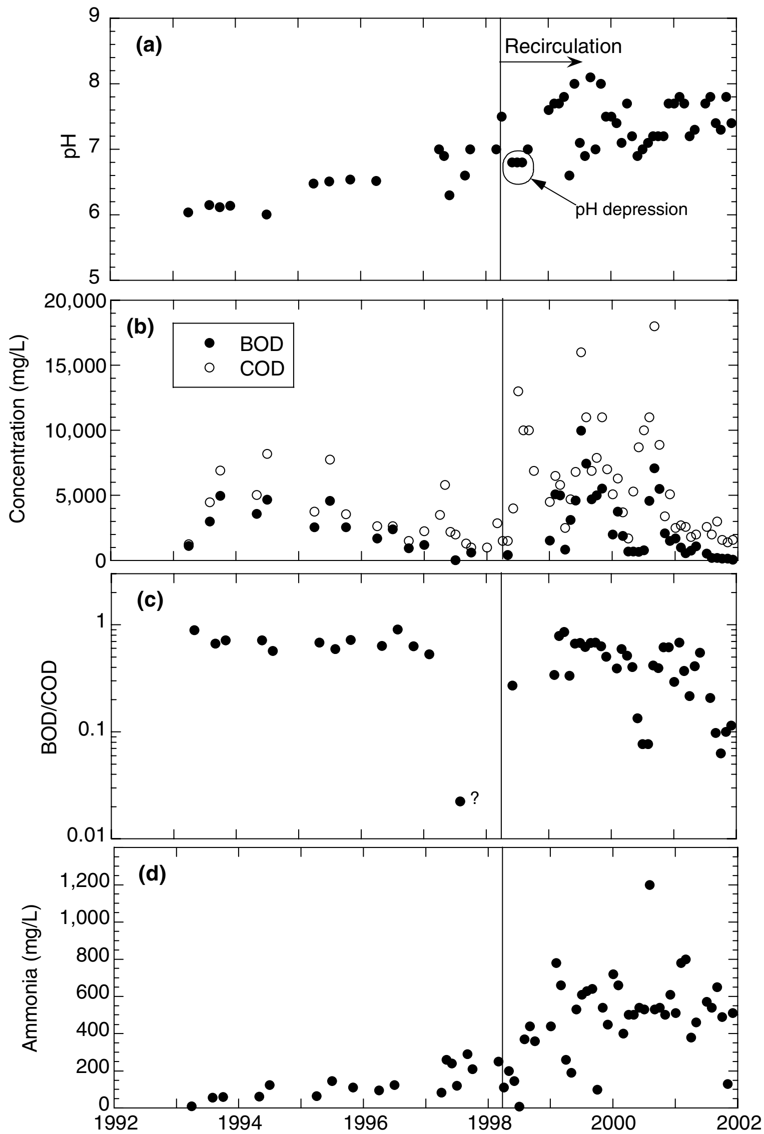

Fig. 10. Leachate quality variables for Landfill C as a function of time: (a) pH, (b) BOD and COD, (c) BOD:COD ratio, and (d) ammonia concentration.

as these landfills were operated conventionally, and then as bioreactors or with recirculation. Landfill D also provides a long-term (20 yr) record of leachate quality from a recirculation landfill and Landfill S provides a side-by-side comparison of leachate quality in conventional and recirculation landfills.

5.1. General characteristics

Leachate quality data for Landfill C are shown in Fig. 10. A very similar data set was obtained for Landfill E (Benson et al., 2003). The trends generally are characteristic of those observed at each of the bioreactor/recirculation landfills. Prior to the initiation of recirculation, the leachate pH increases gradually (Fig. 10a). However, with the onset of recirculation, the pH appears to decrease slightly to about 6.5–6.7 (perhaps due to stimulation of the hydrolytic and fermentative bacteria in the refuse, resulting in an accumulation of carboxylic acids), although considerable scatter exists in the data. The depression in pH lasts for approximately 1 yr, and subsequently the pH increases and then levels off between 7 and 8 (a condition generally favorable for methanogenesis, Zehnder, 1978). A larger decrease in pH (>1 pH unit) was observed for Landfill E at the onset of recirculation and continued for approximately 1 yr (Benson et al., 2003). Insufficient data were available for Landfills S and D to determine if such drops in pH are commonplace after recirculation is initiated.

The COD at Landfill C was decreasing prior to the onset of recirculation, but increased during recirculation (Fig. 10b), most likely as a result of the accumulation of carboxylic acids. BOD also increased at the onset of recirculation. The elevated COD and BOD persisted for approximately 2 yr, 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. The BOD: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 (Fig. 10c), remained essentially the same at the onset of recirculation, and decreased only slightly during the first 3 yr of recirculation. After about 3 yr of recirculation, the BOD:COD ratio began decreasing appreciably. One year later, the BOD:COD ratio reached approximately 0.1, which is characteristic of leachate from well decomposed refuse (Pohland and Harper, 1986).

Ammonia–nitrogen concentrations increased with the onset of leachate recirculation at both Landfills C (Fig. 10d) and E (Benson et al., 2003). The increase in ammonia suggests overall stimulation of biological activity with the onset of leachate recirculation. The ammonia concentration is in the range reported for other landfills (Kjeldsen et al., 2003). Some of the leachate at Landfill C is treated aerobically prior to recirculation, during which a significant portion of the ammonia is converted to nitrate. However, nitrate concentrations are nearly zero in the leachate collected from Landfill C, suggesting that denitrification is occurring in the waste and that the bioreactor is working as a denitrification reactor. This behavior is consistent with theory and previous studies (Onay and Pohland, 1998; Price et al., 2003).

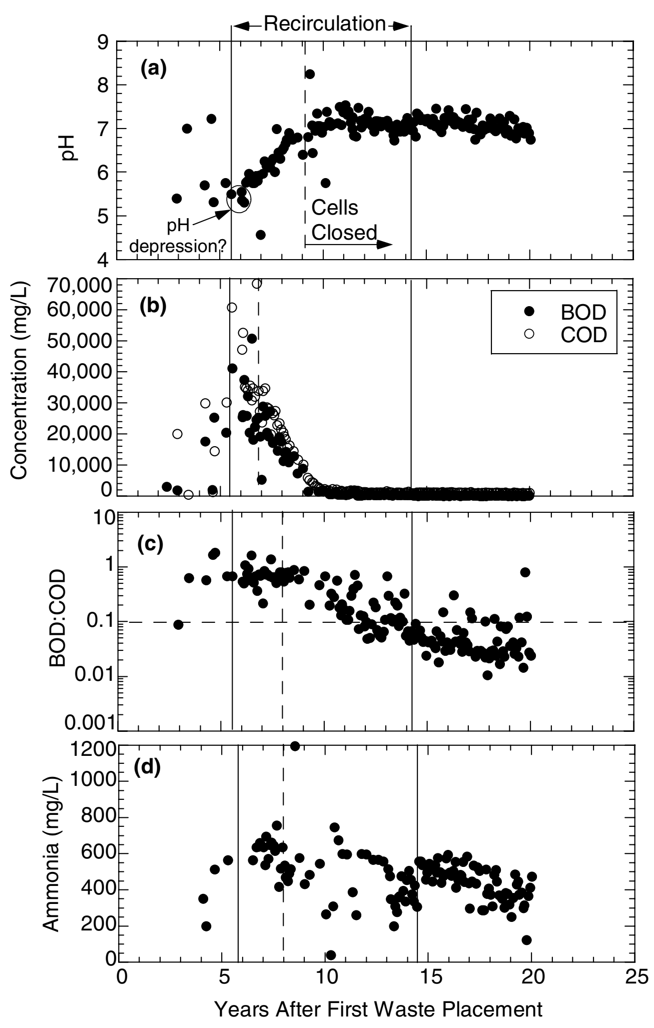

Fig. 11. Leachate quality variables for Landfill D as a function of time: (a) pH, (b) BOD and COD, (c) BOD:COD ratio, and (d) ammonia concentration.

Leachate quality data from Landfill D are shown in Fig. 11. More detailed data on Landfill D are in Morris et al. (2003). A small drop in pH may have occurred after recirculation began at Landfill D (i.e., as at Landfills C and E) (Fig. 11a). Near neutral pH conditions were established approximately 2–3 yr after leachate recirculation began, as occurred at Landfills C and E. BOD and COD increased appreciably after recirculation began (Fig. 11b), dropped appreciably after approximately 2 yr (e.g., as was observed at Landfill C), and then asymptotically decreased to 20–100 mg/L (BOD) and 500–1000 mg/L (COD). The BOD:COD ratio dropped below 0.1 after about 6 yr of recirculation (Fig. 11c). The ammonia concentrations have remained elevated (Fig. 11d), as observed at Landfills C and E, which is consistent with the absence of biological mechanisms for ammonia removal under anaerobic conditions.

5.2. Side-by-side comparison

The leachate quality data from Landfill S (Fig. 12) provide a side-by-side comparison of conventional and recirculation landfills. Although leachate recirculation began at Landfill S in December 1997, leachate quality data were only available from June 1999. The pH climbed gradually in both landfills through 2000 (i.e., approximately 2.5 yr after leachate recirculation began), after which the pH appears to level off between approximately 7 and 8 (Fig. 12a). Since 2001, the pH in both landfills has remained in a range supporting CH_4 production. The pH data also suggest that the microbial population in the recirculation landfill was able to recover from the production of soluble organic matter induced by recirculation.

BOD initially was considerably higher in the leachate from the recirculation landfill, but began declining approximately 2 yr after recirculation was initiated (i.e., as was observed for Landfills C, E, and D). By mid 2002 (~4.5 yr of recirculation), the recirculation and conventional landfills had essentially the same BOD (Fig. 12b). COD showed similar trends (Benson et al., 2003). The elevated BOD in the recirculation landfill is also consistent with the elevated CH_4 production, as discussed previously. The BOD:COD ratios for Landfill S also illustrate the relative difference in BOD between recirculation and conventional landfills (Fig. 12c). The BOD:COD ratio generally is higher for the recirculation landfill, even though the BOD decreased substantially and the pH was neutral. The high BOD:COD ratio may indicate that portions of the waste are still in the acid phase, and that there is a layer of actively methanogenic refuse between the acid-phase refuse and the LCS.

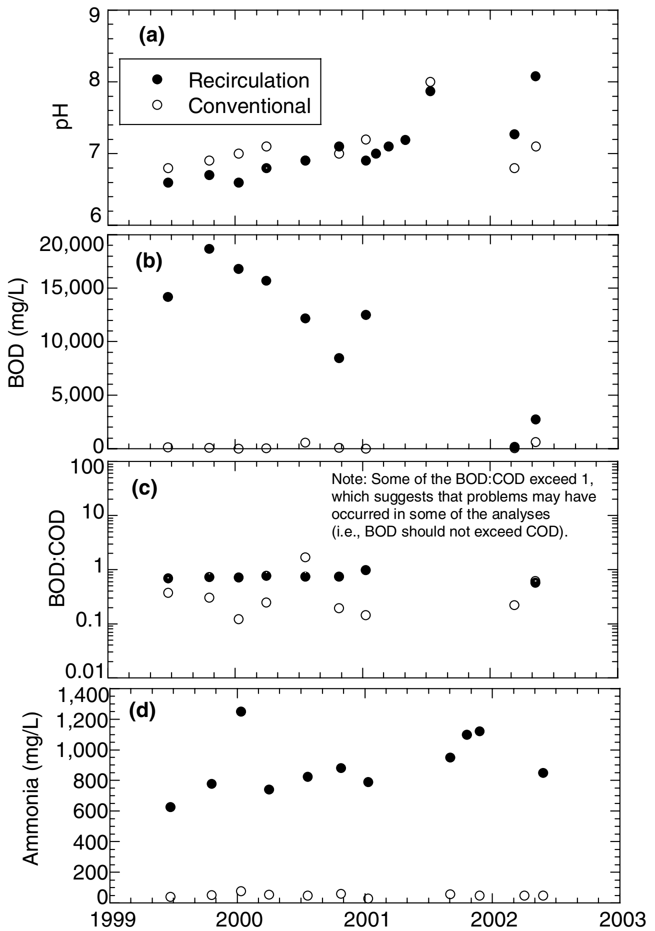

Fig. 12. Leachate quality variables for Landfill S as a function of time: (a) pH, (b) BOD, (c) BOD:COD ratio, and (d) ammonia concentration.

Ammonia concentrations in the recirculation landfill at Site S (Fig. 12d) have remained relatively constant and are appreciably higher than those in the conventional landfill. However, the ammonia concentrations in the conventional landfill are lower than is generally associated with conventional landfills (Kjeldsen et al., 2003). Insufficient data are available to explain why the ammonia concentrations in the conventional cell are unexpectedly low.

6. Settlement

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. Settlement data were available for Landfills S and C. These data were analyzed to determine if bioreactor operations had affected settlement and stabilization of the waste.

At Site S, settlement was monitored using settlement plates placed at the surface of the waste in the conventional and recirculation landfills, 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 in Fig. 13a. Over approximately 1000 days (2.7 yr), waste in the bioreactor settled 22–25%, whereas waste in the conventional landfill settled less than 5%. The rate of settlement in the recirculation landfill also varied with time, with an average rate of approximately 14%/yr during the first 16 mo, and approximately 6%/yr thereafter. In contrast, waste in the conventional landfill settled at a relatively uniform rate of approximately 1.5%/yr.

Settlement data from Landfill C (Fig. 13b) were collected after recirculation began, and thus cannot be used to draw an inference regarding differences between conventional and bioreactor operations. Over a period of 2 yr, the waste at Landfill C has settled 10–15%, with an average

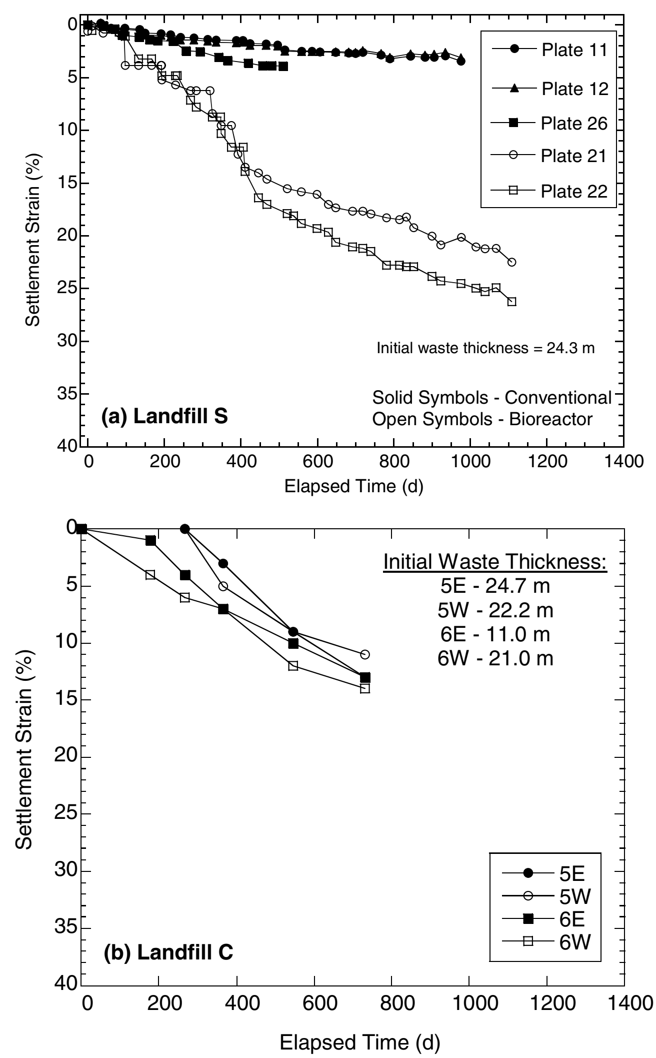

Fig. 13. Settlement strain measured at Landfills (a) S and (b) C using settlement plates. Solid symbols are for the conventional landfill and open symbols are for the bioreactor landfill.

rate of settlement of approximately 7%/yr during the last 18 months of monitoring. Settlements at Landfill C are smaller than those in the recirculation landfill at Site S, but larger than those in the conventional landfill at Site S. The smaller settlements at Landfill C may reflect the smaller fraction of leachate recirculated (Table 6).

7. Summary and conclusions

This study suggests that North American bioreactor and recirculation landfills are operating and functioning in much the same way as conventional landfills, except for the recirculation of leachate and other liquids. However, due to the relatively low rate at which liquids are being circulated in these landfills, none appear to have reached field capacity. Thus, long-term conditions may differ from those observed to date.

All of the landfill designs are consistent with established standards for waste containment in North America. Significant design modifications (e.g., installation of a double liner) to permit bioreactor/recirculation operations were required only at one landfill. Leachate generation rates and leachate depths in LCSs appear no different in bioreactor and conventional landfills, despite the reintroduction of leachate and other liquids. Leachate and liner temperatures appear to be essentially the same in bioreactor and conventional landfills.

At one landfill (Landfill Q), the gas data indicate that degradation of the waste has been accelerated in response to leachate recirculation. Ambiguities in the gas data from the other landfills preclude definitive inferences regarding the effect of bioreactor operations on waste degradation and CH_4 generation. More detailed and carefully collected data regarding CH_4 production, including consideration of gas collection efficiency and waste composition, are needed before reliable conclusions can be drawn regarding the effects of recirculation on decomposition. Interestingly, much larger volumes of liquid are being applied to the waste at Landfill Q. Thus, the amount of liquid recirculated may need to be increased above that commonly used today to accelerate decomposition.

Analysis of typical leachate quality variables (i.e., BOD, COD, ammonia, pH) showed that bioreactors generally produce stronger leachate (elevated BOD, COD, and BOD:COD ratio) than conventional landfills during the first 2–3 yr of recirculation. Thereafter, leachates from conventional and bioreactor landfills appear to become similar. The exception is ammonia, which tends to remain elevated in bioreactor and recirculation landfills. The analysis in this study was limited to conventional wastewater variables (BOD, COD, ammonia, pH); analyses were not conducted to evaluate whether bioreactor operations affected concentrations of metals and VOCs. More study on this issue is needed.

Settlement data collected from two of the landfills indicate that settlements are larger and occur faster in bioreactor landfills. Thus, the waste mass in a bioreactor landfill can be expected to settle more quickly than in a conventional landfill, which should result in better use of permitted airspace during landfill operations and reduced maintenance and operational problems after closure.

The analysis also indicated that more detailed monitoring and more complete and efficient gas collection are needed to draw definitive conclusions regarding the effects of bioreactor and recirculation operations at the full-scale commercial landfills that were studied. For each of the sites in this study, some of the analyses were limited by sparseness or ambiguity in the data sets. More detailed monitoring systems are needed to characterize how the moisture content, gas production, leachate characteristics, and temperature in the waste vary spatially and temporally. More detailed data sets are also needed regarding the settlement of waste and the degradation of solids, both spatially and temporally throughout the waste mass. Data sets of this sort are needed to understand the mechanisms controlling behavior at full-scale and to develop predictive models and tools that can be used for design and performance assessment of the next generation of bioreactor and recirculation landfills.

Acknowledgements

Support for this study was provided by the USEPA under Contract No. 68-C-00-179, Task Order 6. Mr. David Carson was the project manager at USEPA. This document has not been subjected to EPA's peer and administrative review and no endorsement should be inferred. Identities of the landfill bioreactor sites from which data were collected have not been disclosed at the request of some of the owners. Each of the landfills contributed significantly to the study. Some of the individuals who assisted in the study include Anne Germain, Fred Doran, James Norstrom, Mark Reinert, Kevin Wolfe, and Jay Warzinski. The assistance provided by these individuals is greatly appreciated.

References

Barlaz, M., Ham, R., 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., Borden, R., 2002. 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.

Benson, C., 2000. Liners and covers for waste containment. In: Proceedings of the Fourth Kansai International Geotechnical Forum, Creation of a New Geo-Environment. Japanese Geotechnical Society, Kyoto, Japan, pp. 1–40.

Benson, C., Barlaz, M., Lane, D., Rawe, J., 2003. State-of-the-Practice Review of Bioreactor Landfills, Geo Engineering Report 03-05, Department of Civil and Environmental Engineering, University of Wisconsin-Madison.

Bonaparte, R., Daniel, D., 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.

Coops, O., Luning, L., Oonk, H., A. Weenk., 1995. Validation of landfill gas formation models. In: Proceedings of Sardinia'95, Fifth International Landfill Symposium, Cagliari, Italy, pp. 635–646.

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

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

Federal Register, 1991. United States Code of Federal Regulations. 40 CFR Part 258, Subtitle D of the Resource Conservation and Recovery Act (RCRA), Criteria for Municipal Solid Waste Landfills (56 FR 50978). US Government Printing Office, Washington, DC.

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

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

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

Ham, R., 1993. Overview and implications of United-States sanitary landfill practice. Journal of the Air and Waste Management Association 43 (2), 187–190.

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

Klink, R., 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., 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., Blakey, N., 1999. Observations from a review of the Brogborough Landfill 2000 test cell data. In: Proceedings of the 7th International Waste Management and Landfill Symposium, Sardina, Italy. Environmental Sanitary Engineering Centre, Cagliari, Italy, pp. 45–52.

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

Morris, J., Vasuki, N., Baker, J., Pendleton, C., 2003. Findings from long-term monitoring studies at MSW landfill facilities with leachate recirculation. Waste Management 23 (7), 653–666.

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

Pacey, J., Augenstein, D., Morck, R., Reinhart, D., 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, OH.

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

Pohland, F., Harper, S., 1986. Critical Review and Summary of Leachate and Gas Production from Landfills, Report No. EPA/600/2-86/073, US Environmental Protection Agency, Cincinnati.

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

Price, G., Barlaz, M., Hater, G., 2003. Nitrogen management in bioreactor landfills. Waste Management 23 (7), 675–688.

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

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

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

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

USEPA, 1999. Municipal Solid Waste Landfills, vol. 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.

USEPA, 2004. Research, Development, and Demonstration Permits for Municipal Solid Waste Landfills; March 22, 2004, 40 CFR Part 258.

Zehnder, A., 1978. Ecology of methane formation. In: Mitchell, R. (Ed.), Water Pollution Microbiology, vol. 2. Wiley, New York, pp. 349–376.