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THE IMPACT OF LEACHATE RECIRCULATION ON MUNICIPAL SOLID WASTE LANDFILL OPERATING CHARACTERISTICS

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Landfill bioreactor technology offers important advantages in the management and treatment of municipal solid waste, including accelerated waste stabilization rates, enhanced gas production, facilitated leachate management, volume reduction and minimized long-term liability. These advantages have been documented in laboratory- , pilot- and full-scale investigations. Although challenges remain in implementing the technology, bioreactor landfills are designed and operated with increasing frequency. © 1996 ISWA

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1. Introduction

Regulatory and environmental expectations today require a new approach to municipal solid waste (MSW) management and, in particular, to landfill design and operation. As a generality, in the U.S.A., the typical modern landfill is filled rapidly (as a result of high waste receipt rates and cellular design), tends to be quite deep, has an impermeable bottom liner, and is closed with an impermeable cap immediately after filling. These factors tend to limit moisture introduction which is essential to the degradation of organic waste fractions. Without the benefit of adequate moisture, the modern landfill will serve primarily as a temporary storage device with only limited degradation. Once the environmental barriers (caps and liners) fail and permit moisture introduction, the consequential biological activity may result in elevated gas and leachate production and, potentially, adverse environmental impact.

Under proper conditions, the rate of MSW biodegradation in a landfill can be stimulated, enhanced and controlled within certain limits. Environmental conditions which most significantly impact upon biodegradation include pH, temperature, nutrients, absence of toxins, moisture content, particle size and oxidation-reduction potential. Of these, the most critical parameter affecting MSW biodegradation has been found to be moisture content. Once the landfill has been capped, moisture content is regarded as potentially best controlled via leachate recirculation. Leachate recirculation provides a means of optimizing environmental conditions within the landfill, providing enhanced stabilization of landfill contents as well as treatent of leachate moving through the fill. This paper is the first of a two-part series which will describe the implementation of leachate recirculation at full-scale landfills. This paper documents research on the impact of leachate recirculation on waste stabilization, leachate treatment and management, gas

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production enhancement, waste volume reduction and long-term environmental impact. The second paper of this series describes the operating and design characteristics of full-scale bioreactor landfills (Reinhart 1996).

2. Background

Numerous landfill investigation studies (e.g. Pohland & Harper 1986) have suggested that stabilization of waste proceeds in five sequential and distinct phases. The rate and characteristics of leachate produced and biogas generated from a landfill vary from one phase to another, and reflect the microbially mediated processes taking place inside the landfill. The phases experienced by degrading wastes are described below.

2.1 Phase I: Initial adjustment phase

This phase is associated with initial placement of solid waste and accumulation of moisture within landfills. An acclimation period (or initial lag time) is observed until sufficient moisture develops and supports an active microbial community. Preliminary changes in environmental components occur in order to create favourable conditions for biochemical decomposition.

2.2 Phase II: Transition phase

In the transition phase, the field capacity is sometimes exceeded, and a transformation from an aerobic to anaerobic environment occurs, as evidenced by the depletion of oxygen trapped within a landfill media. A trend toward reducing conditions is established in accordance with shifting of electron acceptors from oxygen to nitrates and sulphates, and the displacement of oxygen by carbon dioxide. By the end of this phase, measurable concentrations of chemical oxygen demand (COD) and volatile organic acids (VOA) can be detected in the leachate.

2.3 Phase III: Acid formation phase

The continuous hydrolysis (solubilization) of solid waste, followed by (or concomitant with) the microbial conversion of biodegradable organic content results in the production of intermediate VOAs at high concentrations throughout this phase. A decrease in pH values is often observed, accompanied by metal species' mobilization. Viable biomass growth associated with the acid formers (acidogenic bacteria), and rapid consumption of substrate and nutrients are the predominant features of this phase.

2.4 Phase IV: Methane fermentation phase

During Phase IV, intermediate acids are consumed by methane-forming consortia (methanogenic bacteria) and converted into methane and carbon dioxide. Sulphate and nitrate are reduced to sulphides and ammonia, respectively. The pH value is elevated, being controlled by the bicarbonate buffering system, and consequently supports the growth of methanogenic bacteria. Heavy metals are removed by complexation and precipitation.

2.5 Phase V: Maturation phase

During the final state of landfill stabilization, nutrients and available substrate become limiting, and the biological activity shifts to relative dormancy. Gas production drops dramatically and leachate strength stays steady at much lower concentrations. Reappearance of oxygen and oxidized species may be observed slowly. However, the slow degradation of resistant organic fractions may continue with the production of humic-like substances.

Thus, the progress towards final stabilization of landfill solid waste is subject to the physical, chemical and biological factors within the landfill environment, the age and characteristics of landfilled waste, the operational and management controls applied, and the site-specific external conditions.

3. The impact on leachate characteristics

3.1 Leachate composition

Leachate quality data were collected from five full-scale recirculating landfills [located in Lycoming County, PA; the Central Solid Waste Management Center (CSWMC), Sandtown, DE; the Southwest Landfill, Alachua County, FL; the Central Facility Landfill, Worcester County, FL; and the Breitnau Research Landfill, Austria]. The Lycoming County Landfill (Natale & Anderson 1985), located near Williamsport, Pennsylvania, began operations in mid-1978 with an initial fill area of 12 ha. Leachate recirculation has been practiced since the late 1970s using horizontal trenches. The CSWMC has recirculated leachate since 1982 over three composite lined cells ranging from 3.6 to 8.0 ha in size (Watson 1993). Leachate recirculation has been accomplished using vertical recharge wells, spray irrigation systems and surface application. The Southwest Landfill is a 10.9-ha composite lined facility located in north central Florida (Townsend *et al.* 1994). Leachate recirculation began in late 1990. Initially, infiltration ponds were used to recirculate leachate; in early 1993, a system of horizontal injection lines were constructed for leachate re-introduction. The Central Facility Landfill, a 6.9-ha lined facility, has been recirculating leachate since 1990 using vertical recharge wells. Finally, leachate was recirculated for 3 years over a landfill cell containing 26,000 tonnes of MSW at the Breitnau Research Landfill (Lechner *et al.* 1993).

Results of preliminary analysis of the data are summarized in Tables 1 and 2. Table 1 provides leachate characteristics as a function of landfill stabilization phase for both conventional and recirculating landfills, while Table 2 compares all data. Due to differences in waste age and heterogeneity of conditions found within each landfill, explicit transitions between stabilization phases cannot be determined exactly. Nevertheless, boundaries between such phases were delineated based on the approximate magnitudes of leachate and gas strength [i.e. COD and Biochemical Oxygen Demand (BOD) concentrations, and methane production] obtained from the records at these sites. Furthermore, a comprehensive understanding of stabilization sequence and features, as illustrated in the literature, provided the necessary guidance in dividing the stabilization histograms into their consecutive stages, and projecting the overall values of leachate and gas parameters. From these data, it appears that leachate characteristics of recirculating landfills follow a pattern similar to that of conventional landfills, i.e. moving through phases of acidogenesis methanogenesis and maturation (although few recirculating landfills have reached maturation). These data (as summarized in

TABLE 1
Landfill constituent concentration ranges as a function of the degree of landfill stabilization

Parameter	Phase II		Phase III		Phase IV		Phase V	
	Transition		Acid formation		Methane fermentation		Final maturation	
	Conventional	Recirculating	Conventional	Recirculating	Conventional	Recirculating	Conventional	Recirculating
BOD ($mg\,l^{-1}$)	100–1000	0–6893	1000–57,700	0–28,000	600–3400	100–10,000	4–120	100
COD ($mg\,l^{-1}$)	480–18,000	20–20,000	1500–71,000	11,600–34,550	580–9760	1800–17,000	31–900	770–1000
TVA ($mg\,l^{-1}$ as Acetic Acid)	100–3000	200–2700	3000–18,800	0–30,730	250–4000	0–3900	0	—
BOD/COD	0.23–0.87	0.1–0.98	0.4–0.8	0.45–0.95	0.17–0.64	0.05–0.8	0.02–0.13	0.05–0.08
Ammonia ($mg\,l^{-1}N$)	120–125	76–125	2–1030	0–1800	6–430	32–1850	6–430	420–580
pH	6.7	5.4–8.1	4.7–7.7	5.7–7.4	6.3–8.8	5.9–8.6	7.1–8.8	7.4–8.3
Conductivity ($\mu mhos\ cm^{-1}$)	2450–3310	2200–8000	1600–17,100	10,000–18,000	2900–7700	4200–16,000	1400–4500	—

See text for definitions.

TABLE 2
Leachate constituents of conventional and recirculating landfills

Parameter	Conventional*	Recirculating
Iron (mg l^{-1})	20–2100	4–1095
BOD (mg l^{-1})	20–40,000	12–28,000
COD (mg l^{-1})	500–60,000	20–34,560
Ammonia (mg l^{-1})	30–3000	6–1850
Chloride (mg l^{-1})	100–5000	9–1884
Zinc (mg l^{-1})	6–370	0.1–66

* Pohland & Harper (1986). See text for definitions.

Table 2) do not suggest that contaminants concentrate extensively in the leachate, as has been promoted by critics of leachate recirculation (King 1992). As a matter of fact, the overall magnitude of various leachate components, during the consecutive phases of landfill stabilization, are quite comparable in both types of landfills. However, the acidogenic phase tends to be more pronounced in leachate recycling landfills as opposed to conventional landfills, forming a plateau with consistently high concentrations of leachate constituents (Al-Yousfi 1992). Such a phenomenon can be explained by the fact that uniform, high moisture contact opportunities exist in the leachate recycling landfills. On the other hand, dryness in areas of conventional landfills, accompanied by fewer chances of moisture contact and availability, minimizes the leaching opportunity in such landfills, and results in rapidly peaking leachate washout curves.

Even where recycled leachates are more concentrated than single-pass leachates, they are treated primarily inside the landfill, utilizing its storage and degradation capacity as an effective bioreactor. No extra liability and/or handling requirements will emerge from such cases, because leachate is repeatedly recirculated back into the landfill until its strength diminishes and stabilizes. In this respect, frequency of recirculation can be employed as a new control measure to optimize landfill operations and alter leachate characteristics as desired. Small and less frequent rates of leachate recycling are often practised during the acidogenic phase to avoid any potential inhibitory effects on the overall process. More aggressive recirculation may follow during the methanogenic phase.

Leachate recirculation also has important consequences with regard to metal contamination of leachate. The primary removal mechanism for metals in conventionally operated landfills appears to be washout, although limited chemical precipitation may occur. In leachate recirculating landfills, the primary metal removal mechanisms appear to be sulphide and hydroxide precipitation. Gould *et al.* (1989) found that leachate recirculation stimulated reducing conditions providing for the reduction of sulphate to sulphide, which moderated leachate metals to very low concentrations. Chian & DeWalle (1976) reported that the formation of metal sulphides under anaerobic conditions effectively eliminated the majority of heavy metals in leachate. In addition, neutral or above neutral leachate conditions, promoted by leachate recirculation, enhances metal hydroxide precipitation. With time, moderate to high molecular weight humic-like substances are formed from waste organic matter in a process similar to soil humification. These substances tend to form strong complexes with heavy metals. In some instances, a remobilization of precipitated metals can result from such complexation once the organic content has been stabilized, and oxic conditions begin to be re-established

TABLE 3
Chemical oxygen demand (COD) and chloride half-lives in laboratory- , pilot- and full-scale leachate recirculation studies (years)

Study	COD		Chloride	
	Recirculating	Single-pass	Recirculating	Single-pass
Pohland (1975) (L)	0.21	0.69	0.73	0.29
Pohland (1980) (L)	0.19	–	1.2	–
Tittlebaum (1982) (L)	0.07	3.75	0.43	0.47
Pohland (1992) (L)	0.43	0.41	1.77	0.51
Lechner *et al.* (1993)	0.64	–	–	–
DSWA (1993) (P)	0.32	0.27	1.8*	4.21
DSWA (1993) (F)	1.05	–	2.89	–
Lycoming (1985) (F)	0.78	–	2.58	–

L, laboratory-scale; P, pilot-scale; F, full-scale; DSWA, Delaware Solid Waste Authority. * This value is a doubling time since chloride concentration is increasing.

(Pohland *et al.* 1992). The potential for remobilization supports the idea of inactivating the landfill (removing all excess leachate) once the waste has been stabilized.

Where leachate treatment is the primary objective of wet cell technology, leachate recirculation may be confined to treatment zones located within the landfill where appropriate processes are optimized. Use of *in situ* nitrification, denitrification, anaerobic fermentation and methanogenesis have been proposed to treat leachate, depending on the phase and age of the waste (Pohland 1995). For example, pilot studies in Sweden have successfully investigated a two-step degradation process within a landfill, whereby acidogenic conditions were maintained in one portion of the landfill, and methanogenic conditions were maintained in another part. The high strength, low pH leachate produced within the acid phase area was recirculated to the methane producing area for treatment. Consequently, methane production was accomplished under controlled conditions in an area suitably designed for maximum methane recovery (Lagerkvist 1991).

3.2 Leachate stabilization rates

The rate of waste placement can have a significant impact on leachate characteristics. Waste placed in a laboratory column will behave more or less as described above, following distinct phases of transition, acidogenesis, methanogenesis and maturation. Once methanogenesis is established, the leachate organic strength generally declines. In order to quantify the impact of leachate recirculation of leachate stabilization, a comparison of the rate of decline in the COD for recirculating and single-pass operations was made. Due to the limited available operational information for these studies, a rigorous kinetic analysis of the sequential reactions was not possible. However, a non-linear regression of chronological, declining COD data was performed for a series of laboratory studies of leachate recirculation and conventional, single-pass operations (Pohland 1975; Pohland 1980; Tittlebaum 1982, Pohland *et al.* 1992). From the rate of decline, COD half-lives can be calculated and compared. Half-lives are presented in Table 3, where it can be seen that, in most cases, recirculation accelerated leachate stabilization.

A similar analysis of leachate COD for full-scale leachate recirculating landfills having moved to maturation phases was made with results also provided in Table 3. Here, COD half-lives were nearly five times greater than those of laboratory recirculating lysimeters. A full-scale landfill does not usually depict a single degradation phase, but rather overlapping phases representing various sections, ages and activities within the landfill. In addition, unlike laboratory-scale columns, portions of the full-scale landfill may be relatively dry (due to higher compaction and less efficient recirculation) and experience slower decay rates.

Unfortunately, the relative efficiency of leachate recirculation in enhancing waste degradation relative to conventionally operated landfills at full-scale is difficult to quantify, because of the lack of conventional/recirculation parallel operations. Recognizing this limitation, leachate COD data were gathered from the literature for conventional landfills. The data were analysed to determine a COD half-life as described above (Reinhart 1995). A COD half-life of approximately 10 years was calculated for conventional landfills as compared with values of 230–380 days for recirculating landfills.

Clearly, recirculation significantly increases the rate of the disappearance of organic matter in leachate and, by inference, the rate of waste stabilization. Results for conventional landfills compare favourably with values reported in the literature. Chian & Dewalle (1976) reported effective landfill lives of 10–15 years based on gas production data, and cited half-lives of 36–100 years from the literature. Suflita *et al.* (1992) calculated a half-life of just over a decade for the Freshkills Landfill in New York City based on cellulose: lignin ratios.

Chemical oxygen demand is removed from single-pass landfills via washout and biological conversion, and from recirculating landfills primarily by accelerated biological conversion. A conservative parameter such as chloride would be removed from single-pass landfills via washout. However, in a recirculating landfill, chloride would only be removed when leachate was discharged to treatment and disposal. Therefore, chloride concentration would be expected to decrease over time in a single-pass landfill, while staying relatively constant or declining more slowly in a recirculating fill. Chloride half-lives were calculated as described above for COD and are reported in Table 3 where this behaviour is confirmed quantitatively (i.e. considerably higher chloride half-lives in recirculating fills than in conventional landfills). A comparison of COD and chloride half-lives should provide an independent means of confirming the impact of leachate recirculation on leachate composition, assuming the leachate is evenly distributed and methanogenesis is occurring. The opposite effects of leachate recirculation on the conservative parameter, chloride, and the non-conservative parameter, COD, should provide a COD:chloride half-life ratio of well below 1. For conventional operations, the value should be greater than or equal to 1. Limited data are available to test this hypothesis. However, this trend is seen in Table 4.

4. Gas production

While gas production can be determined accurately from laboratory lysimeters, full-scale measurement of gas emissions from active sites is more difficult to achieve. Data suggest that, as in lysimeters, gas production is significantly enhanced at full-scale landfills as a result of both accelerated gas production rates and the return of organic material in the leachate to the landfill for conversion to gas (as opposed to washout in conventional landfills). Parallel, 1-acre (0·4-ha) cells operated by the Delaware Solid

TABLE 4
Ratios of COD/chloride half-lives (years)

Site	Recirculating	Conventional
Pohland (1975) (L)	0.29	2.38
Pohland (1987) (L)	0.16	–
Tittlebaum (1982) (L)	0.019	1.08
Pohland *et al.* (1992) (L)	0.24	0.8
DSWA (1993) (P)	0	–
DSWA (1993) (F)	0.36	–
Lycoming (1985) (F)	0.30	–

L, laboratory-scale; P, pilot-scale; F, full-scale; DSWA, Delaware Solid Waste Authority.

Waste Authority comparing conventional operation and leachate recirculation showed a 12-fold increase of gas production in the recirculating cell relative to the conventional cell (DSWA 1993). Gas emission measurements at a recirculating landfill in Alachua County, Florida, revealed a doubling of gas production rates from waste located in wet areas of the partially recirculating landfill relative to comparably aged waste in dry areas of the landfill ($0.0236\,m^3\,kg^{-1}\,year^{-1}$ vs. $0.0096\,m^3\,kg^{-1}\,year^{-1}$, Palumbo 1995). This factor was corroborated by comparison of measurements of biological methane potential (BMP) from samples obtained in wet and dry areas of the landfill (Miller *et al.* 1994). A 50% decrease in BMP was measured in wet samples (46% wet basis) over a 1-year period. Negligible decreases in BMP were observed in dry samples (29% wet basis) over the same period.

Gas production enhancement can have positive implications for energy production and environmental impact, but only if gas is managed properly. The facility must be designed to anticipate stimulated gas production, providing efficient gas capture during active phases prior to final capping of the landfill. Captured gas, in turn, must be utilized in a manner which controls the release of methane and non-methane organic compounds and/or provides for beneficial substitution of fossil fuel use.

5. Waste volume reduction

Another consequence of wet cell operation is enhanced subsidence rates. Studies investigating the impact of leachate recirculation on settling have shown that wet cell technology enhances the rate and extent of subsidence. At the Sonoma County, California, pilot-scale landfill, the leachate recirculated cell settled by as much as 20% of its waste depth, while dry cells settled less than 8% (Leckie *et al.* 1979). Wet cells at the Mountain View Landfill, California, settled approximately 13–15%, while control dry cells settled only 8–12% over a 4-year period (Buivid *et al.* 1981). Wetting of waste as it is placed has been practised for many years as a method of increasing compaction efficiency. Rapid and predictable settlement can provide an opportunity to utilize valuable air space prior to closure of the cell. Enhanced degradation rates can provide a means to meet mandated waste volume reduction in some parts of the world. Landfill reclamation and final site use are also facilitated by timely volume reduction provided by moisture control. The difficulty and expense of maintaining the integrity of the final cap over the long term can be reduced as well.

6. Long-term liability

Long-term liability concerns can be minimized if waste is quickly treated to a point where further degradation will not occur, or will occur so slowly that leachate contamination and gas production are sufficiently inconsequential to no longer pose a threat to the environment. A design life of 20 years for geosynthetic membranes may not provide adequate protection for the conventional landfill with stabilization periods of many decades. The potential impact on groundwater from a cleaner leachate is reduced significantly. Similarly, gas production confined to a few years rather than decades provides opportunity for more efficient control and destruction of air toxics and greenhouse gases. With sufficient data, regulators may be convinced to reduce long-term gas, leachate and groundwater monitoring frequency and duration for leachate recirculating landfills, recognizing the reduced potential for adverse environmental impact. Reduced liability (and associated costs required for financial assurance) and minimal monitoring would translate into significant cost savings. A cost saving of about \$U.S.2500 acre (approximately \$U.S.6250 $\text{ha}^{-1}\,\text{year}^{-1}$) is expected at leachate recirculating landfills because of reduced long-term care and liability, the potential for landfill mining and space recovery (Pohland & Al-Yousfi 1984).

7. Conclusions

Data emerging from full-scale recirculating landfills support observations made from pilot- and laboratory-scale investigations, i.e. an acceleration of stabilization processes, leachate management opportunities and enhancement of gas production can be expected during leachate recirculation. As experience is gained in the operation and design of full-scale leachate recirculating landfills, it is expected that advantages of leachate recirculation will become more evident, including economic benefits associated with increased gas utilization opportunities, reduced leachate treatment requirements, avoidance of long-term monitoring and liability, and the potential for landfill mining and re-use.

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