Waste Management & Research (1996) **14**, 347–365

FULL-SCALE EXPERIENCES WITH LEACHATE RECIRCULATING LANDFILLS: CASE STUDIES

Debra R. Reinhart

Civil and Environmental Engineering Department, P.O. Box 162450, University of Central Florida, Orlando, Florida, 32816-2450, U.S.A.

(*Received 15 August 1994, accepted in revised form 18 October 1995*)

Leachate recirculation has been shown in lysimeter, pilot-scale and full-scale investigations to reduce the time required for waste stabilization, improve leachate quality, provide the opportunity for leachate volume reduction, and to enhance the rate of gas production. New generation full-scale landfills are implementing recirculation as a leachate management tool with increasing frequency. Leachate recirculation techniques used at full-scale landfills include pre-wetting of waste, leachate spraying, surface ponds, vertical injection wells and horizontal introduction systems. From observations of operating full-scale recirculating landfills, it appears to be important to provide flexibility in design, minimize low permeability daily and intermediate cover, include adequate *ex situ* storage volume, control infiltration into the landfill, and utilize waste moisture holding capacity efficiently.

Key Words—Leachate, recirculation, landfill, solid waste, waste management, stabilization, water balance, U.S.A., case studies.

1. Introduction

Moisture addition has been demonstrated repeatedly to have a stimulating effect on biological stabilization of municipal solid waste (MSW) placed in landfills. Leachate recirculation appears to be the most effective method to increase moisture content in a controlled fashion. The advantages of leachate recirculation include distribution of nutrients and enzymes, pH buffering, dilution of inhibitory compounds, recycling and distribution of methanogens, liquid storage and evaporation opportunities. It has been suggested that leachate recirculation could reduce the time required for landfill stabilization from several decades to 2–3 years, thus minimizing the opportunity for long-term adverse environmental impact (Pohland 1975).

The effectiveness of leachate recirculation has been well documented in lysimeter studies (Pohland 1975; Tittlebaum 1982; Otieno 1989; Pohland *et al.* 1992), test cell studies at Sonoma County, California; Bingingham, New York; Mountain View, California; Brogborough, U.K.; and Austria (Leckie *et al.* 1979; Wehran Engineering 1987; Halvadakis *et al.* 1988; Campbell 1991; Lechner *et al.* 1993; respectively), and early full-scale attempts in Pennsylvania, the U.K., Germany and Delaware (Natale & Anderson 1985; Robinson & Maris 1985; Doedens & Cord-Landwher 1989; Watson 1993; respectively). However, methods to accomplish leachate recirculation at full-scale sites are still developing, and limited design and operating data are reported in the literature. This paper is the second in a two-part series documenting the use of leachate recirculation at MSW landfills, and provides a description of new generation full-scale landfill bioreactors which have evolved from the earlier studies of the 1970s and 1980s.

0734–242X/96/040347 + 19 $18.00/0

Also presented is a discussion of design and operational issues common to full-scale management of leachate using recirculation.

Leachate recirculation, flow rate and storage data obtained from these landfills are summarized in Table 1. Actual water balances have not been attempted since limited data were available at most sites regarding evaporation, internal storage and moisture loss to gas. The impact of leachate recirculation on gas and leachate characteristics is discussed in detail in the first paper of this series (Reinhart & Al-Yousfi 1996).

2. Case studies

2.1 Southwest Landfill, Alachua County, Florida, U.S.A.

The active Alachua County Southwest Landfill is a 10.9-ha (27-acre) composite lined [0.15 cm (60 mil) high density polyethylene (HDPE) over 30 cm (12 in) of clay] facility located in north central Florida. Waste was first accepted in Spring 1988 and the facility continues to receive approximately 907 tonnes (10,000 U.S. tons) of MSW per month. Maximum landfill depth will be approximately 20 m (65 ft). The landfill is permitted to recirculate up to 227 m^3 day^{-1} (60,000 gallons day^{-1}). Leachate drains by gravity through a leachate collection system to a sump and is pumped to four 341-m^3 (90,000-gallons) storage tanks. Excess leachate is treated using a high lime precipitation process and transported by truck to a local wastewater treatment facility.

Leachate recirculation began in September 1990 through the use of infiltration ponds (see Fig. 1). A section of the landfill was purposely not exposed to leachate recirculation, to provide a comparison to the test area. Over 30 million litres (8 million U.S. gallons) of leachate were recycled to the landfill through the pond system from 1990 to 1992. Infiltration rates averaged between 5.3 and 7.7 l m^{-2} day^{-1} (0.13–0.19 gal ft^{-1} day^{-1}) (Miller *et al.* 1993).

An alternative leachate recirculation system was constructed in early 1993, providing direct injection of leachate into the landfill lifts as they were constructed (see Fig. 2). Horizontal pipes have been placed in 2.4 m (8 ft) wide and 122–213 m (400–700 ft) long trenches filled with tyre chips. The first trench is 6 m (20 ft) above the liner with subsequent trenches added at vertical intervals of 6 m (20 ft) and horizontal intervals of 15 m (50 ft) for a total of 17 laterals. Each lateral has been valved separately to allow rotation of leachate introduction. Leachate was first introduced to the injection system in February 1993. Just over 7.6 million litres (2 million gallons) were pumped to the first two laterals over a period of 6 weeks [310–620 l day^{-1} m^{-1} trench (25–50 gallons day^{-1} ft^{-1})] at a rate of 227–378 l min^{-1} (60–100 gallons min^{-1}) without experiencing pump discharge pressure exceeding 55 kPa. Unlike the ponds, a direct impact on leachate quality and quantity was observed following continuous pumping to the trenches at the initial high rates. From March through September 1993, 757–2950 m^3 $month^{-1}$ (200,000–780,000 gallons $month^{-1}$) were introduced to individual laterals, and no impact on leachate quality was noted. Recirculation laterals were connected to the landfill gas recovery system in early 1994 to permit extraction of gas during the active landfill phase.

2.2 Central Facility Landfill, Worcester County, Maryland, U.S.A.

The Central Facility Landfill, located in Worcester County, Maryland, was constructed in the late 1980s and began operation in 1990. Initially, the first of four 6.9-ha (17-acre) cells was constructed. Maximum fill height will be 27 m (90 ft). Waste receipt

TABLE 1
Full-scale leachate recirculating landfill operating data*

Site	Leachate production (m^3 ha^{-1} day^{-1})	Leachate recirculation (m^3 ha^{-1} day^{-1})	External storage capacity (m^3 ha^{-1})	Off-site treatment (m^3 ha^{-1} day^{-1})	Ultimate design area (ha)	Present active area (ha)
Alachua County	7.8	4.3	124	4.3	11	11
Worcester County	2.6	2.1	220	0.64	6.9	6.9
Winfield County	19.0	13.8	66.8	0.55	2.8	2.8
Pecan Row	2.7	1.1	689	0	16	4.5
Lower Mt.	14.6	9.5	11.7	4.2	3.2	0.45
Washington Valley						
CRSWMA	16.6	11.7	1600	0	8.9	5.7
Landfill						
Lemons	2.2†	5.0	108	NA	30	NA
Mill Seat						
Test Cell 2	2.8†	6.8	35	NA	2.8	NA
Test Cell 3	2.8†	5.2	41	NA	2.2	NA

* Based on present active area and landfill records.
† Estimated using the hydrologic evaluation of landfill performance model, excludes recirculated flow. NA, not applicable.

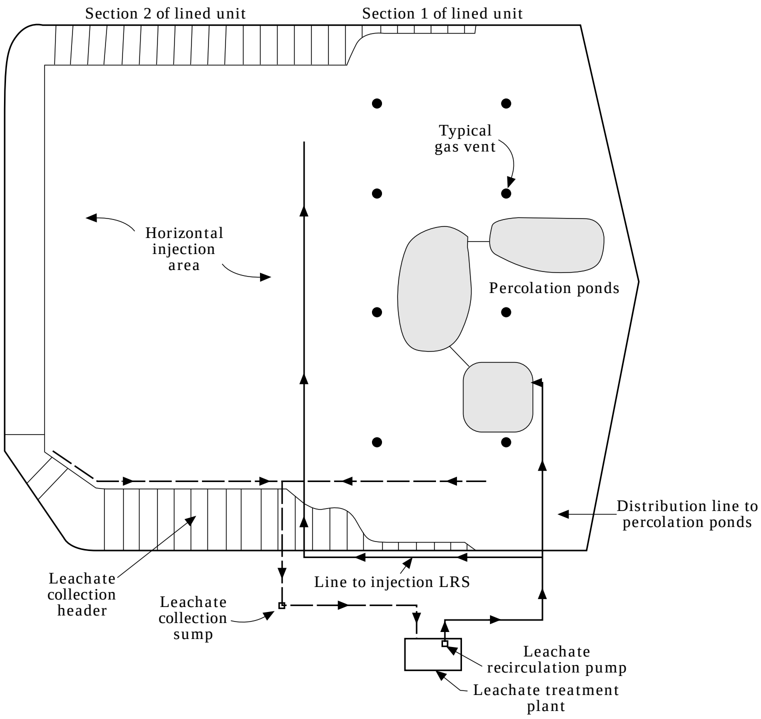


Fig. 1. Leachate recirculation system, Alachua County, Florida Southeast Landfill. ——, leachate recirculation line; –––, leachate collection line.

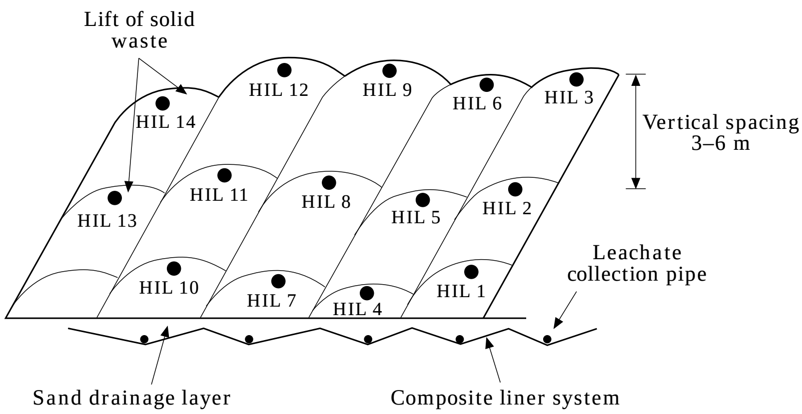


Fig. 2. Horizontal injection lateral (HIL) system, Alachua County, Florida Southeast Landfill.

averages 181 tonnes day^{-1} (200 U.S. tons day^{-1}). The cell is lined with a 0.15-cm (60-mil) HDPE geomembrane installed on top of natural clay soil. Leachate drains through pea gravel to 15-cm (16-in) perforated polyvinyl chloride (PVC) pipes which carry the leachate to sumps located at the four corners of the cell. Leachate is pumped to a 1514-m^3 (400,000-gallon) steel storage tank.

Leachate recirculation is accomplished using vertical discharge wells constructed using 1.2 m (4 ft) diameter perforated concrete manhole sections. The first 2.4-m (8-ft) section rests on a concrete base and is filled with concrete to prevent shortcircuiting of leachate. Subsequent sections are added at each waste lift, then filled with gravel. A 5-cm (2-in) PVC standpipe is installed within each well to vent gas and permit monitoring of water depth. Each well serves a 0.8-ha (2-acre) area. Leachate is pumped to the fill using flexible fire hose which can be dragged to the wells. Surface ponds are also permitted by the State to re-introduce leachate. Usually, these ponds are constructed around the wells and isolated by berms. Estimated construction costs for recirculation facilities were $26,000 (1989 U.S. dollars).

Excess leachate is transported by truck to a local wastewater treatment facility. While minimal off-site treatment has been required, the landfill operators expressed the opinion that the wells have limited impact area, and recommended modifications which would move leachate laterally away from the wells.

2.3 Winfield Landfill, Columbia County, Florida, U.S.A.

The Winfield Landfill located in Columbia County, Florida, opened in September 1992. The double-liner system provided is composed of a 46-cm (19-in) drainage layer, 0.15-cm (60-mil) HDPE geomembrane, and leachate detection system installed over a 46-cm clay soil liner (hydraulic conductivity 10^{-8} cm s^{-1}). The cell is located above natural clay soils. The cell slopes to the southwest to convey leachate to a single corner sump. The present cell area is 2.8 ha (7 acres) with plans for an ultimate footprint of 8.9 ha (22 acres) in four expansion steps. At present, total depth is planned for 16.5 m (54 ft) providing 30–40 years of disposal capacity. Waste receipt averages approximately 109 tonnes day^{-1} (120 tons day^{-1}).

Collected leachate is pumped from the cell to a 189-m^3 (50,000-gallons) aerated lagoon, from which it is either recirculated back to the landfill or tanked off-site for treatment at a local wastewater treatment facility. The facility is permitted to recirculate by surface ponds or spray, provided spraying is limited to a 2-week duration at any one location. In practice, use of surface ponds has been discouraged by regulators. Recirculation is normally accomplished by pumping through one of two permanent headers through PVC lines to sprinkler heads. The spray configuration can be easily dismantled and moved. Spraying is accomplished in areas well separated from operations to an area of approximately 750 m^2 (8000 ft^2). Problems with ponding on the low permeability intermediate cover were reported. More recently, the use of tyre chips for cover has promoted drainage.

Past operation of the landfill permitted all rainfall on the 2.8-ha (7-acre) site to enter the leachate collection system, producing excessive amounts of leachate. The current operation slopes the intermediate cover to the northeast to allow pumping of uncontaminated stormwater to the stormwater collection system. Active areas are bermed to isolate leachate. Recirculation areas are also bermed to avoid contamination of stormwater.

2.4 Pecan Row Landfill, Lowndes County, Georgia, U.S.A.

The Pecan Row Landfill is located in south Georgia near Valdosta. The landfill is located on a 39-ha (97-acre) site with an ultimate fill area of 16 ha (40 acres). Individual 1.5–1.6-ha (3.5–4-acre) cells are constructed approximately every 7 months. Maximum waste depth will be around 18 m (60 ft). The first phase was constructed in 1992 and became operational late the same year. Incoming waste averages around 544 tonnes day^{-1} (600 tons day^{-1}).

The liner system is composed of 0.9 m (3 ft) of on-site recompacted clay overlain by a 0.15-cm (60-mil) HDPE geomembrane, geonet, geotextile and, finally, 0.61 m (2 ft) of drainage sand. Leachate collection pipes convey leachate to a shallow, double-lined 3100-m^3 (821,000-gallon) lagoon.

Leachate recirculation is accomplished by pumping [at 1514 l min^{-1} (400 gallons min^{-1})] through three 15-cm (6-in) polyethylene force mains to the fill area. The recirculation system is shown schematically in Fig. 3. Corrugated, perforated lateral pipes branch off the force mains at 45° angles at 30-m (100-ft) intervals. The pipes are placed in 0.9–1.2 m (3–4 ft) deep, 0.9 m (3 ft) wide gravel-filled trenches dug into the waste with a backhoe. A separate recirculation system is provided at each waste lift. A total of 457-m (1500-ft) of pipe were installed in 4.5 ha (11 acres) of landfill area.

Leachate is normally pumped for 1 h, then discontinued for 1 h. As of Spring, 1994, all leachate generated has been stored or recirculated as a result of high rates of evaporation from the large lagoon. To minimize leachate generation, 0.03-cm (12-mil) polyethylene sheeting is used as temporary cover over areas not receiving waste. In addition, the temporary cover is used over fill areas as daily cover. Weekly soil cover is required by the state. The cover material is removed prior to placing waste, to maintain good moisture routing through the waste. Should excess leachate accumulate, trucking to a nearby wastewater treatment facility is planned.

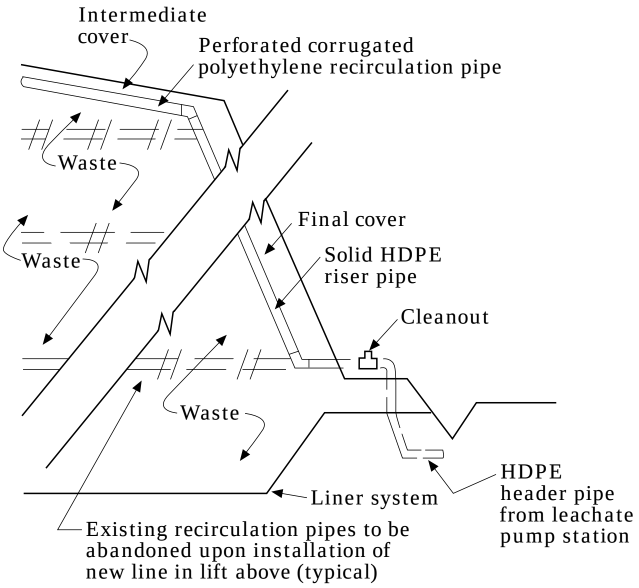
It was observed that once the waste has been wetted thoroughly, an immediate impact on pond level can be seen following each subsequent pumping. Difficulty was encountered in recirculating during early operational phases when insufficient waste was available to absorb the moisture. Also, recirculation near the waste surface or slope led to leachate outbreaks.

2.5 Lower Mount Washington Valley Secure Landfill, Conway, New Hampshire, U.S.A.

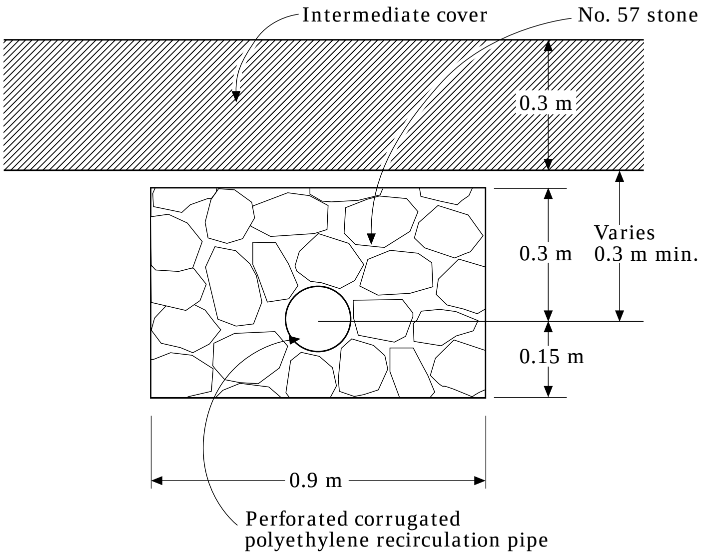
The Lower Mount Washington Valley Secure Landfill, located in Conway, New Hampshire, is composed of eight hydraulically separated double-lined landfill cells [0.3–0.4 ha (0.75–1.0 acres)]. Cell construction was completed in late 1991, with operations commencing in January 1992. Waste receipt averages between 9070 and 13,600 tonnes year^{-1} (10,000 and 15,000 tons year^{-1}). Leachate is stored in a 37.8-m^3 (10,000-gallon) leachate collection tank.

Leachate recirculation began in May 1992 at the first of eight cells, 4 months after start-up. The primary mode of leachate recirculation was manual pre-wetting of waste using a fire hose to improve compaction and wet the waste efficiently. In addition, recirculation has been accomplished using a fabricated PVC pipe manifold placed in a shallow excavation of the daily cover.

In order to minimize lateral movement of leachate, horizontal trenches were installed on waste slopes for leachate recirculation into these areas. The trenches were 1.4–1.8 m (4–6 ft) deep, 0.9–1.2 m (3–4 ft) wide, and 2.4–4.6 m (8–15 ft) long. However, short-circuiting resulted due to the proximity of the sand drainage layer and this practice was discontinued. High leachate generation rates were experienced during Spring 1993, which were attributed to saturation of the fill while recirculating during the previous



Leachate recirculation pipe detail



Recirculation line detail

Fig. 3. Leachate recirculation system, Pecan Row Landfill, Valdosta, Georgia.

fall and winter, followed by freezing and then the spring thaw. Consequently, leachate recirculation was discontinued temporarily in November 1993. To date, leachate recirculation has not resulted in excessive head on liner. Efforts have been made to minimize precipitation infiltration, through the use of alternative daily cover, and to maximize use of waste moisture holding capacity. Gas measurements suggested that leachate recirculation stimulated biodegradation of waste.

2.6 Coastal Regional Solid Waste Management Authority Landfill, Craven County, North Carolina, U.S.A.

The Coastal Regional Solid Waste Management Authority Landfill serves three counties along the eastern coast of North Carolina. Waste receipt averages around 318 tonnes day^{-1} (350 tons day^{-1}). The 8.9-ha (22-acre) landfill is divided into three hydraulically separated cells of approximately equal surface area. Final height is expected to be around 15 m (50 ft). A composite liner composed of 0.6 m of drainage sand, a fabric filter and a 0.15-cm (60-mil) HDPE liner overlying 0.6 m (24 in) of low permeability clay were provided. A drainage system was installed beneath the liner system to protect the liner during periods of high groundwater level. Weekly cover consists of local sandy soils. The active face is covered daily with re-usable tarp. Leachate from each cell drains by gravity to manholes which are connected to a common sump. Leachate is pumped from the sump to one of two 4.54 million-litre (1.2 million-gallon) lined lagoons [4.6 m (15 ft) maximum depth]. Each lagoon is equipped with two floating mechanical aerators to provide oxygen for biological treatment of leachate.

Leachate is pumped back to the first lift of waste [depth approximately 4.6 m (15 ft)] through 152 m (500 ft) of flexible hose feeding a movable vertical injection system. A steel manifold distributes leachate through 12 flexible lines to shallow black iron probes inserted into the landfill surface. Flow to each line is controlled by individual ball valves. Initially, the 1.9 cm (0.75 in) diameter probes were 1.5 m (5 ft) in length, with 0.32 cm (0.125 in) diameter holes drilled within 0.76 m (2.5 ft) of the bottom of the pipes. Probes are installed by driving solid pipes of similar diameter into the ground to form a hole and then inserting the probes. Early use of these probes resulted in leachate breakout at the slopes. Longer probes [3 m (10 ft)] were fabricated to minimize breakout. The diameter was increased to 3.2 cm (1.25 in) with 0.64 cm (0.25 m) diameter holes. Breakouts continue to occur occasionally. Leachate recirculation pump flow rates vary between 208 and 303 l min^{-1} (55 and 80 gallons min^{-1}) to an area approximately 30 m by 30 m (100 ft by 100 ft). Once leachate is observed at the surface near the probes, the system is moved. Generally, the system stays in any one location for 2–8 days. Pressure at the recirculation manifold is monitored and remains around 310 kPa (45 psi).

Once the entire first lift is completed, horizontal trenches will be constructed in a pattern radiating out from a central distribution box fed by the leachate recirculation pump. The horizontal system will be used until the second lift is completed, at which time a new distribution system will be installed and the first system will be abandoned. This procedure will continue until the fourth and final lift is completed and the landfill is closed.

2.7 Lemons Landfill, Stoddard County, Missouri, U.S.A.

The Lemons Landfill is located on a 66-ha (162-acre) site in Stoddard County, Missouri. The fill area at build-out will be 30 ha (75 acres). Maximum depth will be 26 m (85 ft).

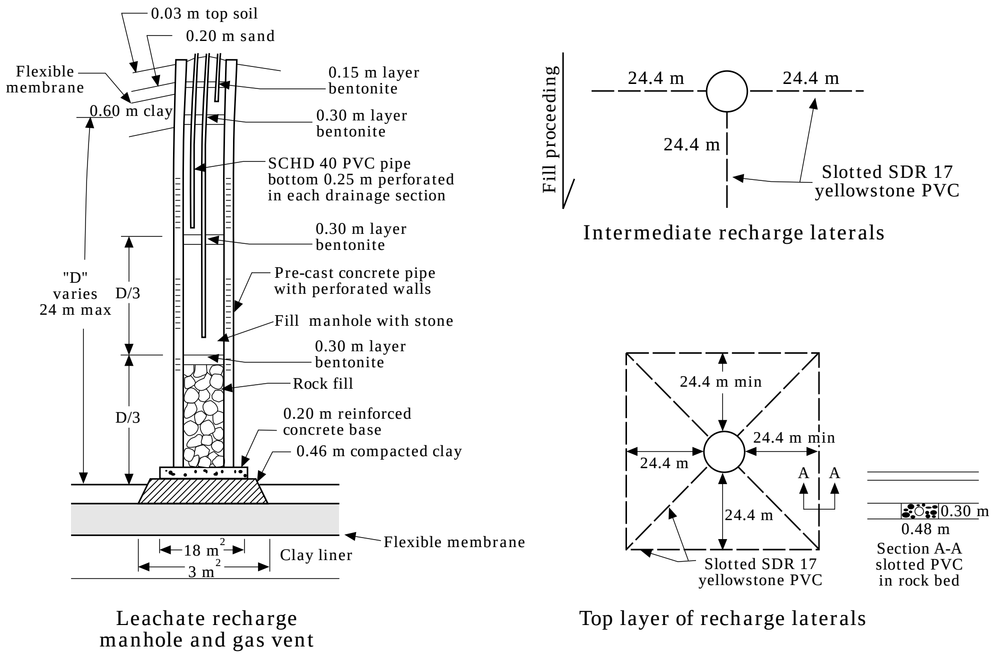


Fig. 4. Leachate recirculation system, Lemons Landfill, Stoddard County, Missouri.

Waste is received at a rate of approximately 272 tonnes day^{-1} (300 tons day^{-1}). The landfill was constructed in 1993 and began operating in October of that year. A composite liner was provided, composed of a 0.15-cm (60-mil) PVC geomembrane on top of 0.6 m (2 ft) of compacted bentonite/soil, overlain with 30 cm (12 in) of pea gravel and perforated PVC piping for conveyance of leachate. Leachate is collected in two ponds which provide total storage of 3280 m^3 (867,800 gallons).

Leachate recirculation will be accomplished using vertical wells located at 61-m (200-ft) intervals within the fill area (see Fig. 4). Recirculation will be delayed until the area is filled and capped temporarily with 0.6 m (2 ft) of clay. Recirculation is expected to commence approximately 1 year following initial waste receipt. The leachate recirculation well is constructed from a 1.2 m (48 in) diameter pre-cast perforated concrete pipe filled with 5–10 cm (2–4 in) diameter stone. Within the structure are 30-cm (12-in) bentonite caps separating the well into three sections. PVC pipes [10 cm (4 in) diameter] are inserted into the wells reaching each of the three sections. The well structure rests on a 1.8-m^2 (6-ft^2) concrete pedestal underlain with a 10 cm (4 in) diameter PVC plotted pipe placed in 30 cm by 46 cm (12 in by 18 in) trenches] radiating out from each well at two depths.

Once leachate recirculation commences, it will be collected in the first of two available storage ponds. Recirculation will continue until leachate strength is reduced significantly. At this point, leachate will be diverted to the second pond and subsequently used to irrigate completed areas of the fill [capped with 0.6 cm (2 ft) of clay, 0.075-cm (30-mil) PVC geomembrane, and 0.3 m (1 ft) of topsoil and seeded].

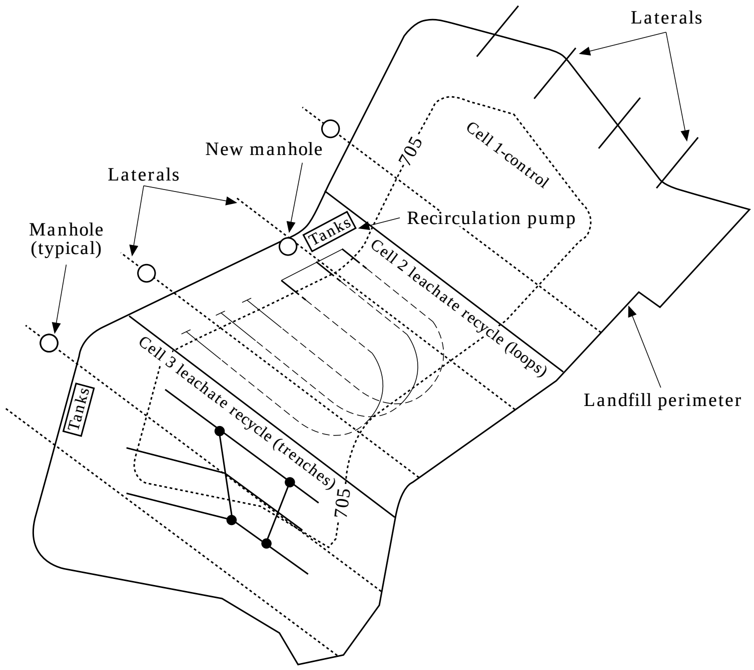


Fig. 5. Leachate recirculation system, Mill Seat Landfill, Monroe County, New York. ●, vertical recharge; ––, perforated pipe; …., solid pipe; ——, recirculation trenches/infiltrators.

2.8 Mill Seat Landfill, Monroe County, New York, U.S.A.

The Mill Seat Landfill, located in western New York, near Rochester, is hosting a bioreactor research project involving the design, construction and monitoring of leachate recirculation in three hydraulically separated double composite lined cells. One cell [3 ha (7.4 acres)] serves as a control (gas collection only), while two test cells [2.8 ha (6.9 acres) and 2.2 ha (5.4 acres), respectively] use two different recirculation techniques. Leachate pH control will be instituted if necessary. The test cells will provide an opportunity to evaluate effects of leachate recirculation on the rate of waste stabilization, the quality of the leachate produced, and the volume of methane emitted. The three test cells comprise Stage I of the landfill which will ultimately have a 38-ha (95-acre) footprint and a total waste depth of up to 34 m (110 ft).

Leachate recirculation is accomplished using two different horizontal introduction systems (see Fig. 5). The first system, installed in Test Cell 2, uses three pressurized loops constructed from 10 cm (4 in) diameter perforated HDPE pipe laid in trenches filled with crushed cullet, tyre chips or other permeable material. The loops will be provided at three elevations within the cell. Collected leachate will be directed to tanks providing a total of 114 m^3 (30,000 gallons) of storage, from which it will be pumped back to the pressurized loop system.

The second recirculation technique, used in Test Cell 3, provides 1.3 m (4 ft) wide by 3 m (10 ft) deep horizontal trenches filled with permeable wastes and installed at two elevations. Pre-fabricated infiltrators placed within the trenches will enhance leachate distribution. As waste is placed on top of the trenches, chimneys will be constructed to allow continued feeding of leachate to the trenches. Leachate will be introduced to the vertical chimney/wells via a tanker truck and pump. Leachate from Test Cell 3 is directed to tanks providing 76 m^3 (20,000 gallons) storage. Pre-wetting of waste on occasion using water distribution trucks will also be practised.

Recirculation rates are expected to be between 19 and 114 m^3 day^{-1} (5000 and 30,000 gallons day^{-1}). The relative moisture content of the waste will be monitored using gypsum blocks located *in situ* at depths of 10.6, 19.8 and 29 m (35, 65 and 95 ft) above the landfill liner. Gas recovery will be accomplished from both the pressurized loop system and the chimneys. In addition, vertical gas wells will be installed at closure. Gas will be either flared or used to generate electricity.

2.9 Additional full-scale efforts

Leachate has been recirculated at the Fresh Kills Landfill on Staten Island, New York, since 1986. The landfill is not lined (although it is underlain by a thick layer of low permeability natural clays) and has no leachate collection system; therefore, recirculation was discontinued in late 1993. Seeps at the toe of the landfill required the installation of French drains constructed of crushed stone surrounding perforated pipe all wrapped in filter fabric. Collected leachate was pumped to the top of the landfill to a seep field dug into the waste and constructed in a similar fashion to the drain system. Each seep field served a 15 m by 15 m (50 ft by 50 ft) area and was valved so that recirculation could be rotated from one area to another. An estimated 530 m^3 (140,000 gallons day^{-1}) were recirculated to an area of 20–34 ha (50–60 acres) [averaging 24 m^3 day^{-1} (2545 gallons $acre^{-1}$ day^{-1})]. No clogging of the crushed stone was observed after operating for 5 years.

Recirculation is also practised at the Gallatin National Balefill in Fairview, Illinois, where leachate is sprayed daily onto exposed waste surfaces using a water truck. In addition, perforated piping is installed at several elevations to provide a distribution network which will double as a horizontal gas extraction well. The Kootenai County Fighting Creek Landfill in Idaho uses two systems for applying leachate. One system pumps leachate from the two aerated lagoons [total storage 4353 m^3 (1,150,000 gallons)] and spray irrigates areas of the landfill which have been temporarily covered and seeded to maximize the evapotranspiration opportunity during summer months. Year round, leachate will be pumped from collection headworks to a subsurface system, composed of horizontal perforated pipes installed at 30 m (100 ft) spacing under the final cover and vertical wells spaced at 91 m (300 ft).

Several full-scale bioreactor test programmes are currently taking place in Sweden including a two-step degradation study conducted at Lulea, an integrated landfill gas project involving landfills in Helsingborg, Stockholm and Malmo, and the SORAB "Energy Loaf" study in northern Stockholm (Brundin, 1991; Lagerkvist 1991*a*,*b*).

Two cells containing 450 m^3 (15,900 ft^3) of waste each were constructed recently in Viborg, Denmark, to evaluate biogas production potential and enhancement methods. One cell contains only household waste, the second cell contains household waste and yard waste, with leachate recirculation provided in both cells (Willumsen 1991). Leachate recirculation is also being investigated in southern Italy where experiments are being conducted with distillation of leachate, recirculation of the distillate, and biological treatment of the condensate (Cossu & Urbini 1989). In Canada, previous concepts of dry storage are changing, and leachate injection is being promoted (Fergusen 1989). The Rosedale Landfill in New Zealand has been recirculating leachate since the mid

1980s, and leachate recirculation is planned at the Greenmount Landfill, the largest landfill in New Zealand. In San Pedro Sula, Honduras, a 250 tonnes day^{-1} (225 tons day^{-1}) landfill has been constructed to recirculate leachate using a low technology methodology (Gonzales 1994). Leachate will be introduced at the top surface of the fill, and will be intercepted as it runs down the mound slope by pipes which convey leachate to high permeability intermediate cover provided at the top of waste lifts.

3. Discussion

3.1 Leachate introduction systems

The efficiency of leachate distribution and waste moisture absorption varies with the device used to recirculate leachate. Full-scale methods currently employed include pre-wetting of waste, spraying, surface ponds, vertical injection wells and horizontal infiltration devices. These methods also differ in leachate recirculating capacity, volume reduction opportunities, and compatibility with active and closed phases of landfill operation.

3.1.1 Pre-wetting of waste

Pre-wetting of waste has been practised for many years as a method for increasing compaction efficiency. More recently, leachate has been used as the wetting agent. Waste wetting is most commonly accomplished using water tankers (Doedens & Cord-Landwehr 1989), or by manual spraying using a fire hose. In addition to compaction enhancement, pre-wetting has advantages in terms of simplicity, evaporation opportunity, and a uniform and efficient use of waste moisture holding capacity. This technique has been rarely used in large-scale operations. Obviously this technique cannot be used following landfill closure, when it would be replaced by some form of subsurface injection.

3.1.2 Leachate spraying

Recirculation of leachate via surface spraying has been practised at the Seamer Carr Landfill in the U.K. (Robinson & Maris 1985), landfills in Delaware (Watson 1993), the Kootenai County Fighting Creek Landfill in Idaho, and the Winfield Landfill in Florida. Problems were encountered at the Seamer Carr landfill with the development of a solid hard-pan at the surface. Surface furrowing was necessary to increase infiltration rates. Leachate blowing and misting with associated odour and potential health problems were described by Watson (1993); problems which have led many state regulators to ban spraying of leachate. Doedens & Cord-Landwehr (1989) only recommend spraying when COD is below 1000 mg l^{-1}, and they observed that flows were reduced by 75% when spray was utilized. Leachate spraying is quite flexible; the systems can be constructed to be easily moved from one area to another to maximize application rates and avoid active areas. Spraying provides the greatest opportunity for volume reduction of all recirculation methods used to date. Spraying cannot be used during periods of rain or freezing conditions, and is not compatible with the application of an impermeable cover at closure.

3.1.3 Surface ponds

Leachate recirculation using surface infiltration ponds has been used successfully at several landfills in Florida and with less success in Delaware. Ponds collect stormwater and can be the source of odours, although this has not been reported to be a problem at Florida landfills. Unless moved frequently, ponds will have limited recharge areas. This was illustrated by recent data from the Alachua County site where waste moisture content below the pond was an average 46% of wet weight, while moisture content in areas immediately adjacent to the pond was only 29% (Miller *et al.* 1994). Again, surface ponds will not be compatible with an impermeable final landfill cover.

3.1.4 Vertical injection wells

Vertical wells were, at one time, the most popular engineered approach to leachate recirculation, and are used at the Worcester County Landfill, in Delaware landfills (Watson 1993), the Lemons Landfill and the Kootenai County Fighting Creek Landfill. Well spacing varies from one well per 0.16 ha to one well per 0.8 ha. If wells are spaced too closely, they may interfere with waste placement and compaction. Concern has also been expressed over possible tearing of the bottom liner if the well rests on the geomembrane, as well as problems with well integrity during landfill subsidence. Generally the bottom section of the well is not perforated to minimize leachate shortcircuiting. Infiltration rates also appear to be enhanced if rest periods are provided between pumping events.

3.1.5 Horizontal subsurface introduction

Horizontal subsurface introduction has been used at the Alachua County Southwest Landfill, the Lower Mount Washington Valley Secure Landfill, the Fresh Kills Landfill, the Pecan Row Landfill and the Lycoming Landfill in Pennsylvania (Natale & Anderson 1985). Horizontal infiltrators (hollow half pipes imbedded in gravel) are used in landfills in Delaware (Watson 1993), and the Mill Seat Landfill in New York. Typical horizontal devices are shown in Fig. 3. In all cases, horizontal trenches are dug into the waste and filled with a permeable material such as automobile fluff (Lycoming County), gravel (Delaware and Fresh Kills) or tyre chips (Alachua County). Leachate is either fed to perforated piping by gravity, or injected. Horizontal systems can be used during active phases of the landfill, or at closure if constructed as part of the cover system. Both Alachua County and New Hampshire sites reported that overuse of trenches led to significant increases in leachate collection rates, as well as spikes in leachate component concentration. Landfill subsidence may adversely affect horizontal systems. Large quantities of leachate can be successfully introduced to trenches, although long-term use may result in biofouling of trench fill materials and a consequent reduction in permeability.

3.1.6 Device placement

The present trend in designing bioreactor landfills is to provide either horizontal or vertical systems, or a combination of horizontal and vertical systems. Design criteria for placement of introduction devices is scarce and typically based on prior experience. Other issues remain uncertain in designing for full-scale leachate recirculation, including the determination of the area of influence of recirculation devices, the effect of leachate recirculation on leachate collection systems, and appropriate recirculation flow rates. Townsend (1994) recommends at least 3 m of waste placed on top of a horizontal injection line, and 6 m distance from side slopes to avoid leachate outbreaks and artesian conditions at the surface of the fill. French drains may be necessary at landfill slopes to control side seeps. Miller *et al.* (1991) also selected a 6-m spacing for trenches based on results of excavation studies at a recirculating cell operated by the Delaware Solid Waste Association. Intermittent introduction, permitting a fill and drain operation, can also prevent saturated conditions from developing.

Vertical injection appears to be required in conjunction with a horizontal system to wet a landfill efficiently. Due to the limited impact area and the cone-shaped impact volume of both devices, a combination of vertical and horizontal devices should be considered. Alternative placement of trenches at right angles to each other at each lift may also increase the impact area. Wicks are being used at several landfills to increase the impact area.

3.2 Liner/leachate collection system

The conventional liner/leachate collection system utilizes a composite, double or double composite liner with geosynthetic and natural soil components. Some states, such as New York and Pennsylvania, require double composite liners irrespective of leachate management technique. The drain is perhaps the most critical element of the collection system, and generally consists of highly permeable natural materials such as sand or gravel, or a geosynthetic net. The drain must be protected by a natural soil or geosynthetic filter to minimize clogging due to particulates in the leachate and biological growth. Koerner & Koerner (1995) concluded in a recent study that the filter should be the focus of concern in the leachate collection system because of a reduction in permeability over time. Filter clogging is expected and difficult to control, therefore Koerner & Koerner suggest the use of a safety factor in selecting the design filter permeability, and recommend the placement of a geotextile over the entire landfill footprint rather than wrapping the collection pipe. Koerner & Koerner also expressed concern over the possibility that bioreactor operations may encourage clogging by stimulating biological processes within the cell.

The drain should be designed to accept the excess flows expected during leachate recirculation. The depth of leachate on the liner is a function of the drainage length, liner slope, permeability of the drain and the liner, and the rate of moisture impingement. Under normal conditions, studies using the Hydrologic Evaluation of Landfill Performance (HELP) model have shown that the depth of the liner is much less than the liner thickness, and is primarily a function of the liner permeability (McEnroe & Schroeder 1988). Field experiences with leachate recirculation have encountered excess heads on the liner, but only when *ex situ* storage and treatment is limited in capacity.

3.3 Leachate storage

In order to gain the benefits of leachate recirculation, leachate/waste contact opportunity must be provided at a rate which does not cause leachate to accumulate excessively within the landfill, or emerge from landfill slopes and contaminate stormwater runoff. Proper management of leachate requires an understanding of a recirculating landfill water balance. Precipitation falling on an active landfill will either infiltrate, runoff or evaporate. Once moisture enters the landfill, moisture holding capacity within the landfill may be sufficient to delay the appearance of leachate. Leachate generation begins when this capacity is exceeded or, more likely, when shortcircuiting occurs due to the heterogeneity in permeability within the landfill. In addition, substantial leachate flows can be generated during the active landfill phase from areas where the leachate

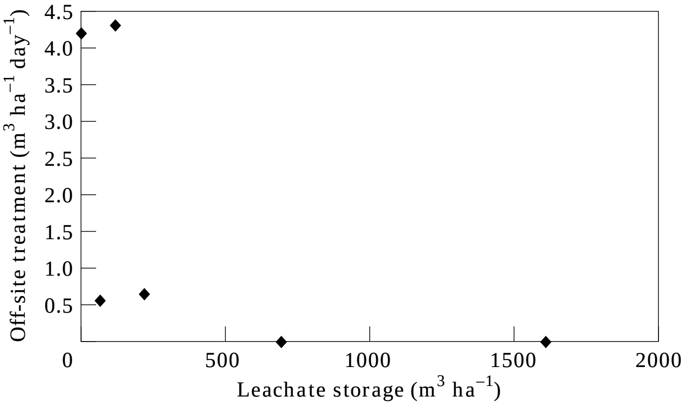


Fig. 6. Effect of leachate storage on off-site treatment requirements.

collection system is not covered by waste and there is no opportunity for absorption. In many landfills, these areas are isolated using berms at the waste face and through piping and valving arrangements which allow uncontaminated water entering the leachate collection system to be diverted to stormwater management facilities.

Once filling has commenced, intermediate or final cover can be sloped so as to divert large portions of precipitation to stormwater management facilities. In some instances, plastic sheeting or carpet have been used to provide temporary cover and minimize infiltration. In any case, *ex situ* liquid storage is vital to proper management of leachate during early phases of landfill operation, during peak storm events, and following closure of the cell (but prior to inactivation of the cell). In some areas, of course, precipitation rates are so low that ensuring sufficient moisture to wet the waste adequately is more problematic than managing leachate.

The impact of storage on off-site management requirements can be seen in Fig. 6, where data from full-scale operational sites described in this paper are plotted. At sites where large storage volumes were provided relative to the size of the landfill cell, off-site leachate management was minimized. From this figure, storage volume in excess of 700 $m^3\,ha^{-1}$ appears to be necessary to manage leachate. Doedens & Cord-Landwehr (1989) recommended storage volumes of 1500–2000 $m^3\,ha^{-1}$ in their investigations of German full-scale leachate recirculating landfills. The New York Department of Environmental Conservation requires storage for 3 months' leachate generation.

Sites with relatively little storage were also compelled to recirculate at much higher rates than those with large storage volumes. Figure 7 shows the relationship between leachate generation and recirculation. As expected, as recirculation rates increase, greater volumes of leachate are produced, and recirculated leachate represents an increasing percentage of generated flows (asymptotically approaching 100%). It would appear that sites with little *ex situ* storage are, in effect, using the landfill itself (the waste, drainage layers and the leachate collection and recirculation piping) as a storage vessel. Such *in situ* storage is not necessarily bad, if ponding is avoided and heads on liner are controlled. In fact, in operations where moisture holding capacity of the waste is used appropriately and open areas are minimized, *in situ* storage of leachate may be adequate to manage infiltrating moisture, even during early phases of landfill operation. Doedens & Cord-Landwehr (1989) estimated that the additional storage provided from

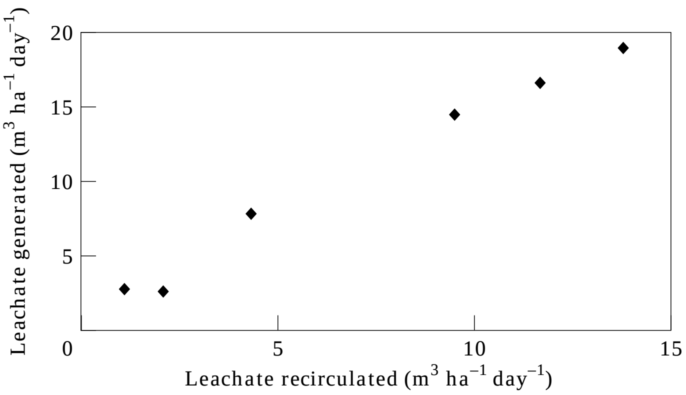


Fig. 7. Effect of leachate recirculation on leachate generation.

homogeneous distribution of introduced leachate amounted to some 10 times the volume of leachate generated. However, in situations where large areas are open during early phases of landfill operation, infiltration can lead to ponding within the landfill and excessive head on the liner if *ex situ* storage and/or off-site management is not sufficient to permit timely removal of leachate.

Storage facilities must be sized both to provide adequate capacity during precipitation events and to ensure the availability of sufficient volumes of leachate to recirculate at an effective rate (Baetz & Onysko 1993). Baetz & Onysko recommend setting the volume of storage at the maximum of two volumes; the volume required to recirculate when no precipitation has occurred (a function of the time between storm events and leakage through the liner), and the volume of leachate generated during a peak storm event (a function of the intensity and duration of the storm and the area collecting precipitation). When precipitation exceeds the design storm event, off-site treatment is required. It has been observed, however, that no matter how much storage has been provided at a landfill, it is never enough according to those who must operate the site.

3.4 Intermediate cover and final caps

As moisture moves through the landfill, heterogeneity in permeability will be encountered frequently, leading to horizontal movement and the potential for leachate ponding or side seeps. The introduction of daily or intermediate cover of low permeability can be particularly troublesome when attempting to introduce large volumes of leachate to the site. Outbreaks and ponding of leachate were reported at the Seamer Carr Landfill investigation (Robinson & Maris 1985). Accumulations within the site to depths of 1.2 m or more were reported due to the use of low permeability soil cover. Natale & Anderson (1985) also reported saturated conditions and ponding at the Lycoming County site during periods when high volumes of leachate were recirculated in areas using clay and silty soils for daily cover. Personnel at full-scale sites including the Worcester County Landfill, the Lower Mount Washington Valley Secure landfill, Pecan Row Landfill, the Coastal Regional Solid Waste Management Authority Landfill and the Winfield Landfill all reported side seeps and/or ponding due to horizontal movement of leachate. In order to minimize ponding and horizontal movement, use of highly permeable soils and/or alternative daily cover should be considered, as well as the removal of soil cover prior to waste placement.

The typical landfill today is closed within 2–5 years and, because of high construction costs, is built to depths of well over 100 m, minimizing exposed surface area. In addition, many states prohibit the disposal of yard waste in landfills, eliminating a significant source of moisture. As a consequence, calculations show that even if emplaced waste captures every drop of precipitation in the wettest climates, moisture content of the waste at closure may be below optimum levels for biological degradation (Leszkiewicz & McAulay 1995). In reality, much of the water entering a landfill finds highly permeable pathways to the collection system, and is not absorbed by the waste. Once closed, further introduction of moisture is prevented by impermeable caps. As degradation proceeds, moisture content continues to decline with losses to biological uptake and gas, and waste degradation may slow further. Postponement of final closure should be considered to allow for placement of an interim cap which provides for both limited infiltration of moisture and leachate recirculation to maintain appropriate conditions for biodegradation of waste.

3.5 Cell construction

For economic reasons, the recent trend in landfill construction is to build deep cells which provide a life of less than 5 or 6 years. This trend also has certain advantages related to bioreactor design. Designs can incorporate latest technological developments rather than committing long term to a design which may prove to be inefficient. Small, hydraulically separate cells are easier to isolate to minimize stormwater contamination and shed water more efficiently when covered. Baetz & Byer (1989) calculated that as much as 30% more leachate is generated from horizontal cell construction when compared with extreme vertical construction with minimal face exposure. Once closed, methanogenic conditions within the cell optimize, and gas production and collection is facilitated. It may also be possible to use the closed cell to treat leachate from new cells. Deep cells improve compaction, and anaerobic conditions are more readily established. However, moisture content in small, deep cells may be lower than optimum; therefore, leachate recirculation is essential to efficient waste degradation.

4. Conclusions

The characteristics of eight full-scale leachate recirculating landfills (six of which are currently in operation at time of writing) provided important insights regarding design and operating parameters. Redundancy in leachate recirculation technology provides the flexibility to manage large volumes of leachate under a variety of operating conditions. Sufficient *ex situ* leachate storage is also of critical importance to minimize off-site leachate management requirements. Storage in excess of 700 $m^3\,ha^{-1}$ may be necessary in some situations. Smaller storage volume leads to a higher frequency of leachate recirculation, which may be a factor in creating side seeps and local ponding. Horizontal leachate re-introduction systems appear to be gaining in popularity, and provide an efficient means of introducing large volumes of leachate. The potential for clogging of horizontal systems and the impact of landfill settling on system integrity must be examined during long-term use.

Full-scale use of leachate is becoming increasingly common in the United States and other parts of the world. Each application provides additional information necessary to identify optimum design and operating criteria for successful operation. With continued use of this technology, it is expected that regulators, designers, owners and operators of landfills will recognize the advantages associated with leachate recirculation and use it confidently to manage leachate where appropriate.

Acknowledgements

The research described herein has been financed in part by Federal funds under Cooperative Agreement 820316 with the Risk Reduction Engineering Laboratory of the United States Environmental Protection Agency (USEPA). This paper has not been subjected to the Agency's peer and administrative review and, therefore, the contents do not necessarily reflect the views and politics of the USEPA, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

References

Baetz, B. W. & Byer, P. H. (1989) Moisture control during landfill operation. *Waste Management & Research* **7**, 259–275.

Baetz, B. W. & Onysko, K. A. (1993) Storage volume sizing for landfill leachate recirculation systems. *Journal of Environmental Engineering* **119**, 378–383.

Brundin, H. (1991) The SORAB test cells. In *Landfill Gas Enhancement Test Cell Data Exchange, Final Report of the Landfill Gas Expert Working Group* (P. Lawson, ed.). Report for the International Energy Agency, Harwell Laboratory, Oxfordshire, U.K.

Campbell, D. J. V. (1991) U.K. Brogborough Test Cell Project. In *Landfill Gas Enhancement Test Cell Data Exchange, Final Report of the Landfill Gas Expert Working Group* (P. Lawson, ed.). Report for the International Energy Agency, Harwell Laboratory, Oxfordshire, U.K.

Cossu, R. & Urbini, G. (1989) Sanitary landfilling in Italy. In *International Perspectives on Municipal Solid Wastes and Sanitary Landfilling* J. S. Carra & R. Cossu, eds). London, U.K.: Academic Press.

Doedens, H. & Cord-Landwehr, K. (1989) Leachate recirculation. In *Sanitary Landfilling: Process, Technology and Environmental Impact* (T. H. Christensen, R. Cossu & R. Stegmann, eds). London, U.K.: Academic Press.

Fergusen, R. G. (1989) Sanitary landfilling in Canada. In *International Perspectives on Municipal Solid Wastes and Sanitary Lanfilling* (J. S. Carra & R. Cossu, eds). London, U.K.: Academic Press.

Gonzales, A. J. (1994) An Integrated System for Leachate Reintroduction and Gas Venting. Presented at the 1994 GEOENVIRONMENT 2000 Conference, New Orleans, LA, U.S.A.

Halvadakis, C. P., Findikaki, A. N., Papelis, C. & Leckie, J. O. (1988) The mountain view controlled landfill project field experiment. *Waste Management & Research* **6**, 103–114.

Koerner, G. R. & Koerner, R. M. (1995) Permeability of Granular Drainage Material. Presented at the U.S. EPA Bioreactor Landfill Design and Operation Seminar, Wilmington, Delaware, U.S.A.

Lagerkvist, A. (1991*a*) Test cells in Sweden, status report, October 1991. In *Landfill Gas Enhancement Test Cell Data Exchange, Final Report of the Landfill Gas Expert Working Group* (P. Lawson, ed.). Report for the International Energy Agency, Harwell Laboratory, Oxfordshire, U.K.

Lagerkvist, A. (1991*b*) Two step degradation—an alternative management technique. *Proceedings Sardinia '91, Third International Landfill Symposium*, Calgari, Italy.

Lechner, P., Lahner, T. & Binner, E. (1993) Reactor Landfill Experiences Gained at the Breitenau Research Landfill in Austria. Presented at the 16th International Madison Waste Conference, Madison, Wisconsin, U.S.A.

Leckie, J. O., Pacey, J. G. & Halvadakis, C. (1979) Landfill management with moisture control. *Journal of the Environmental Engineering Division, Proceedings of the American Society of Civil Engineers*, **105**, 337–355.

Leszkiewicz, J. & McAulay, P. (1995) Municipal Solid Waste Landfill Bioreactor Technology Closure and Post-Closure. Presented at the US EPA Seminar: Landfill Bioreactor Design and Operation, Wilmington, Delaware, U.S.A.

McEnroe, B. M. & Schroeder, P. R. (1988) Leachate collection in landfills: steady case. *Journal of Environmental Engineering* **114**, 1052–1062.

Miller, L. V., Mackey, R. E. & Flynt, J. (1991) Evaluation of a 30-ml PVC Liner and Leachate Collection System in a 10 Year Old Municipal Solid Waste Landfill. Presented at the 29th Annual Solid Waste Association of North America Solid Waste Exposition.

Miller, W. L., Townsend, T., Earle, J., Lee, H., Reinhart, D. R. & Paladugu, P. (1993) Leachate Recycle and the Augmentation of Biological Decomposition at Municipal Solid Waste Landfills. Presented at the First Annual Research Symposium, Florida Center for Solid and Hazardous Waste Management, Orlando, Florida, U.S.A.

Miller, W. L., Townsend, T., Earle, J., Lee, H. & Reinhart, D. R. (1994) Leachate Recycle and the Augmentation of Biological Decomposition at Municipal Solid Waste Landfills. Presented at the Second Annual Research Symposium, Florida Center for Solid and Hazardous Waste Management, Tampa, Florida, U.S.A.

Natale, B. R. & Anderson, W. C. (1985) Evaluation of a Landfill with Leachate Recycle. Draft Report to US EPA Office of Solid Waste, Washington, D.C., U.S.A.

Otieno, F. O. (1989) Leachate recirculation in landfills as a management technique. *Proceedings Sardinia '89, Second International Landfill Symposium*, Calgari, Italy, C. XII-1–C.XII–9.

Pohland, F. G. (1975) Accelerated solid waste stabilization and leachate treatment by leachate recycle through sanitary landfills. *Progress in Water Technology* **7**, 753–765.

Pohland, F. G., Cross, W. H., Gould, J. P. & Reinhart, D. R. (1992) The Behavior and Assimilation of Organic Priority Pollutants Codisposed with Municipal Refuse. EPA Co-operation Agreement CR-812158, Volume 1. Cincinnati, OH, U.S.A.: U.S. Environmental Protection Agency.

Reinhart, D. R. & Al-Yousfi, A. B. (1996) The impact of leachate recirculation on municipal solid waste landfill operating characteristics. *Waste Management & Research* **14**, 337–346.

Robinson, H. D. & Maris, P. J. (1985) The treatment of leachates from domestic waste in landfill sites. *Journal of the Water Pollution Control Federation* **57**, 30–38.

Tittlebaum, M. E. (1982) Organic carbon content stabilization through landfill leachate re-circulation. *Journal of the Water Pollution Control Federation* **54**, 428–433.

Townsend, T. (1994) *Leachate Recycle at the Southwest Landfill Using Horizontal Injection.* PhD Thesis, University of Florida, U.S.A.

Watson, R. P. (1993) Active Landfill Management. Presented at the Modern Double Lined Landfill Management Seminar, Saratoga Springs, New York, U.S.A.

Wehran Engineering, P.C. & Dynatech Scientific, Inc. (1987) Enhancement of Landfill Gas Production, Nanticoke Landfill, Binghamton, New York, (U.S.A.), New York State Energy Research and Development Authority, *NYSERDA Report 87–I9.*

Willumsen, H. C. (1991) Registration and Optimizing of Gas Production from Closed Waste Test Cells in Landfills. In *Landfill Gas Enhancement Test Cell Data Exchange, Final Report of the Landfill Gas Expert Working Group* (P. Lawson, ed.). Report to the International Energy Agency, Harwell Laboratory, Oxfordshire, U.K.