Chapter 7
Landfill Bioreactor Design

Introduction

In many ways, the design of the modern MSW landfill is dictated by state and federal regulation (primarily RCRA Subtitle D regulations). The design components most critical to the landfill include the liner and leachate collection system, leachate management facilities, gas collection and management, and the final cap. These same components must be adapted to the landfill bioreactor to manage greater volumes of leachate, to incorporate leachate reintroduction, and to handle enhanced gas production. This chapter addresses each of these components, providing design guidance for adapting to bioreactor operation, based on current practice. For more complete landfill design guidance the reader is referred to the many documents addressing this topic, *i.e.*, US EPA, 1989; Bagchi, 1994; Tchobanoglaus, et al; 1993; McBean, et al, 1995. Since bioreactor technology is in its infancy, this chapter will reflect state-of-the-art practice; improvements in the design are expected and desired.

Liner/Leachate Collection System

The conventional liner/leachate collection system utilizes a composite, double, or double composite liner with geosynthetic and natural soil components. The landfill bioreactor requires a carefully designed liner system to accommodate extra leachate flow. At a minimum, a composite liner should be provided as encouraged by Subtitle D of RCRA. Some states, such as New York and Pennsylvania, require double composite liners irrespective of the leachate management technique employed.

The drainage system, located above the liner, 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 as well as biological growth. Koerner and 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 results from sedimentation, biological growth, chemical precipitation and/or biochemical precipitation, and is quite difficult to control. Clogging is most often experienced during the acidogenic period when organic substrates and precipitating metals such as calcium, magnesium, iron, and manganese are most highly concentrated in the leachate (Giroud, 1996). High substrate concentration stimulates biological growth and the development of biofilms which become encrusted with inorganic precipitates. Since leachate recirculation promotes a shorter acidogenic phase and enhances metal removal in the waste mass, it may be assumed that recirculation would reduce the potential for clogging. Koerner and Koerner, however, expressed concern over the possibility that bioreactor operations may encourage clogging by stimulating biological processes within the cell. Koerner and Koerner suggest use of a safety factor in selecting the design filter permeability and recommend placement of a geotextile over the entire landfill foot print rather than wrapping the collection pipe. Waste with low concentrations of fines should be placed in the first layer on top of the filter.

Giroud (1996) makes the final recommendation for filter selection to minimize the risk of clogging:

- sand filters and nonwoven geotextile filters should not be used,
- if a filter is used, a monofilament woven geotextile (perhaps treated with a biocide) with a minimum filtration opening size of 0.5 mm and a minimum relative area of 30 percent should be selected, and
- the drainage medium should be an open-graded material, such as gravel, designed to accommodate particle and organic matter passing through the filter.

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 Model (HELP) model have shown that the depth of the head on the liner is much less than the liner thickness and is a function primarily of the drain permeability (McEnroe and Schroeder, 1988). Field experience with leachate recirculation have encountered excess heads on the liner on occasion, however only when ex situ storage and treatment is limiting (discussed further in following sections).

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, run off, 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 short-circuiting 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 collection system is not covered by waste and there is no opportunity for moisture absorption by the waste. 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 and minimize leachate production. In some instances, plastic sheeting has been used to provide temporary cover and minimize infiltration. 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 the country, of course, precipitation rates are so low that ensuring sufficient moisture to adequately wet the waste is more problematic than managing leachate.

The impact of storage on off-site management requirements can be seen in Figure 7-1, where data from full-scale operational sites described in Chapter 5 are plotted. As discussed in Chapter 6, at sites where large storage volumes were provided relative to the size of the landfill cell, off-site leachate management was minimized. Sites with relatively little storage recirculated at higher rates than those with large storage volumes. From Figure 7-1, storage in excess of 700 m^3/ha (75,000 gal/acre) appears to be necessary to manage leachate. Doedens and Cord-Landwehr (1989) recommended storage volumes of 1500 to 2000 m^3/ha (160,000 to 210,000 gal/acre) in their investigations of German full-scale leachate recirculating landfills. The New York Department of Environmental Conservation requires storage for three month's leachate generation.

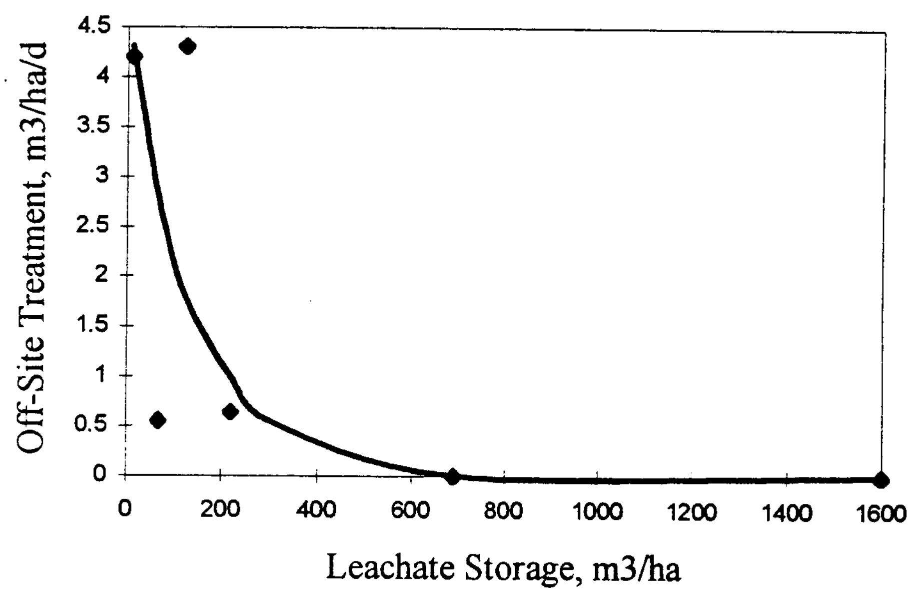

Figure 7-1. Effect of leachate storage on off-site treatment requirements.

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 detrimental if ponding is avoided and heads on the liner are controlled to meet regulatory requirements. In fact, in operations where moisture holding capacity of the waste is appropriately used 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 and Cord-Landwehr (1989) estimated that the additional storage provided from homogeneous distribution of reintroduced leachate amounted to some ten 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 and Onysko, 1993). In any case, storage should exceed 700 m^3/acre in wet climatic areas. When precipitation exceeds the design storm event, off-site treatment will be required and accommodations for transport and treatment of these flows must be made. It has been observed, however, that leachate storage facilities have been frequently undersized, leading to excessive head on the liner, ponding, side seeps, and costly transportation of leachate for ex situ treatment.

Baetz and Onysko (1993) provided a more quantitative method of sizing storage facilities based on a simple hydrologic balance about a recirculating landfill. The methodology assumes the moisture absorption capability of the landfill is exhausted. Primary flows in and out of the landfill involve precipitation, recirculated flows, leakage through the liner, and leachate removed from the storage facility for ex situ management. They also assume that the storage facility is empty at the start of each precipitation event and full at the end of the event. They recommend setting the volume of storage at the maximum of two volumes: the volume required to recirculate when no precipitation has occurred (to compensate for 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). The first volume (V_1) can be calculated as the product of the leakage rate through the liner and a design precipitation interevent time:

$$V_1 = Q_l \, t_{ie} \, 3{,}600$$

Where:

V_1	=	volume for first condition (m^3)
t_{ie}	=	design precipitation interevent time (hrs)
Q_l	=	leakage rate (m^3/sec)

Q_l can be determined using Darcy's Law or empirical formulae developed for leakage through composite liners (Giroud, et al , 1989).

The second volume (V_2) can be calculated by determining the percolation rate, Q_P, and the design precipitation event duration.

$$Q_p = \frac{i_d P A}{1{,}000 \cdot 3{,}600}$$

Where:

Q_P	=	percolation rate (m^3/sec)
i_d	=	design precipitation intensity (mm/hr)
P	=	percolation factor (the fraction of rainfall that percolates out through the base of the cover
A	=	area, m^2

$$V_2 = Q_P t_e 3{,}600$$

Where:

V_2	=	volume for second condition (m^3)
t_e	=	duration of precipitation event

The design volume is then the maximum of V_1 and V_2.

The methodology can be illustrated by the following example. A 5-ha (12-acre) hypothetical landfill is underlain by a low permeability soil liner. The percolation factor is 0.2. Design rain intensity is 100 mm/hr (4 in/hr), lasting 2.8 hrs (a 25-yr storm). The time between events averages 38.3 hrs. The leakage rate is estimated at 5×10^{-5} m^3/sec (0.8 gpm). The percolation rate is calculated to be 3.5×10^{-3} m^3/sec (56 gpm). Therefore, the volume for the first condition is 7 m^3 (1,900 gal) and the second, 2,700 m^3 (720,000 gal). The design volume, therefore, is driven by the storm event (as would be expected) and is 2,700 m^3 (720,000 gal).

Leachate Reintroduction Systems

The efficiency of leachate distribution and waste moisture absorption varies with the device used to recirculate leachate. Full-scale methods currently employed include prewetting 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. The advantages and disadvantages of each method are summarized in Table 7-1. Table 7-2 provides a listing of hydraulic application rates used at full-scale operating sites.

Prewetting of Waste

Prewetting of waste has been practiced 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 and Cord-Landwehr, 1989) or by manual spraying using a fire hose. In addition to compaction enhancement, prewetting has advantages in terms of simplicity, evaporation opportunity, and a uniform and efficient use of waste moisture

Table 7-1. Comparison of Frequently Used Leachate Recirculation Devices.

Recirculation Method	Disadvantages	Advantages
Prewetting	- labor intensive - blowing of leachate - enhances compaction (may interfere with leachate routing) - incompatible with closure	- simple - uniform and efficient wetting - promotes evaporation
Vertical Injection Wells	- subsidence problems - limited recharge area - interference with waste placement operations	- relatively large volumes of leachate can be recirculated - low cost materials - easy to construct during and following waste placement - compatible with closure
Horizontal Trenches	- potential subsidence impact on trench integrity - potential biofouling may limit volume - inaccessible for remediation	- low cost materials - large volumes of leachate can be recirculated - compatible with closure - unobtrusive during landfill operation
Surface Ponds	- collect stormwater - floating waste - odors - limited impact area - incompatible with closure	- simple construction and operation - effective wetting directly beneath pond - leachate storage provided
Spray Irrigation	- leachate blowing and misting - surface precipitation leads to decreased permeability - cannot be used in inclement weather - incompatible with closure	- flexible - promotes evaporation

Table 7-2. Full-Scale Leachate Recirculation Hydraulic Application Rates

Recirculation Method	Application Rates	Source/Comments
Prewetting	0.2 m^3/ m ton compacted waste (593 kg/tone)	CMA Engineers, 1993
Vertical Injection Wells	(A) 0.23 to 0.57 m^3/hr per 6.4 cm diameter well 0.07 to 0.17 m^3/m^2 landfill area/day	(A) Merritt, 1992 - noncontinuous injection rate industrial landfill, hydraulic conductivity 10^{-2} cm/sec
	(B) 4.6 to 46 m^3/hr per 1.2 m diameter well 0.005 to 0.09 m^3/m^2 landfill area/day	(B) Watson, 1993 - noncontinuous injection rate municipal landfill, estimated hydraulic conductivity 10^{-4} cm/sec
Horizontal Trenches	0.31 to 0.62 m^3/m of trench length/day at 14 to 23 m^3/hr	Miller, et al, 1993 (early in application period)
Surface Ponds	0.0053 to 0.0077 m^3/m^2-day	Townsend, 1992
Spray Irrigation	(A) 0.73 m^3/m^2 of landfill area/day (B) 0.001 to 0.0032 m^3/m^2 of landfill area/day	(A) Watson, 1993 (intermittent application) (B) Robinson and Maris, 1982

holding capacity. This technique has been rarely used in large-scale operations because of its labor intensive nature. Obviously this technique cannot be used following landfill closure, when it would be replaced by some form of subsurface injection.

Leachate Spraying

Recirculation of leachate via surface spraying has been practiced at the Seamer Carr landfill in England (Robinson and Maris, 1985), and 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 due to chemical precipitation of leachate constituents when exposed to air. Therefore, surface furrowing was necessary to increase infiltration rates into the landfill. Leachate blowing and misting as well as odor problems were described by Watson, problems which have led many state regulators to ban spraying of leachate. Doedens and Cord-Landwehr (1989) recommend spraying only when COD is below 1000 mg/l and observed that flows were reduced by 75 percent 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 applications 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.

Surface Ponds

Leachate recirculation using surface infiltration ponds has been successfully accomplished at several landfills in Florida and with less success in Delaware. Ponds are simple to construct and operate by removing one to two meters of waste and introducing leachate. However they consume significant portions of the active landfill which are not available for waste disposal. Ponds collect stormwater and can be the source of odors, although this has not been reported to be a problem at Florida landfills, perhaps due to the lower organic strength of Florida leachates. Unless moved frequently, ponds will have limited recharge areas, as was illustrated by recent data from the Alachua County site where waste moisture content below the pond averaged 46 percent of wet weight while moisture content in areas immediately adjacent to the pond was only 29 percent (Miller, et al, 1994). Floating waste have been a problem at the Alachua site as well, leading to the abandonment of ponds in favor of a horizontal injection system. As with other surface introduction methods, ponds will not be compatible with an impermeable final landfill cover.

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 anywhere from one well per 0.10 ha (0.25 acre) of surface area to one per 0.8 ha (2 acres). 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 directly 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 short circuiting. Usually the wells are installed as each lift of waste is placed by stacking sections of large diameter perforated concrete pipe (frequently manhole sections). Typical vertical wells are shown in Figures 5-4 and 5-8. Infiltration rates also appear to be enhanced if rest periods are provided between pumping events.

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 and 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 Figures 5-6 and 5-11. In all cases, horizontal trenches are dug into the waste and filled with a permeable material such as automobile waste (Lycoming County), gravel (Delaware and Fresh Kills) or tire chips (Alachua County) surrounding a perforated pipe (HDPE or PVC). Leachate is either fed to perforated piping by gravity or injected under pressure. 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 concentration spikes. Landfill subsidence may adversely affect the integrity of horizontal systems although no evidence of this problem has been found to date. Large quantities of leachate can be successfully introduced to trenches, although long-term use may result in biofouling of trench fill materials and a consequential reduction in permeability.

Device Placement
Based on an evaluation of available information the most practical and efficient recirculation methodology uses horizontal devices, vertical devices, or a combination of horizontal and vertical systems. Design criteria for placement of reintroduction 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. A United States Geological Survey (USGS) software package entitled SUTRA (Saturated and Unsaturated Transport Model), a finite element simulation model for saturated/unsaturated flow, was modified to model the hydrodynamics of leachate flow through a landfill following introduction of leachate using vertical and horizontal introduction devices. This program generates isoclines of pressure and saturation data which have been used to develop design guidance.

The application of SUTRA is described in more detail in Appendix C, results and conclusions pertinent to system design are provided herein. Modeling assumptions included steady-state and transient operation, homogeneous and isotropic medium, and constant leachate input and outflow. The model is two dimensional (vertical and one transverse direction). A landfill is neither homogeneous nor isotropic, and intermittent liquid introduction is a normal operating mode for leachate recirculation. However, the results of this modeling effort provided useful insight into the impact of the rate of leachate reintroduction, the depth of the landfill, and the waste permeability on

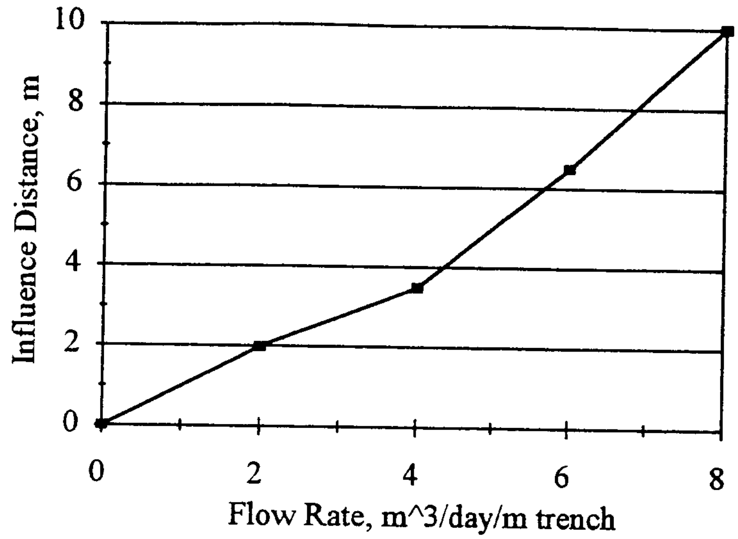

Figure 7-2. Influence distance of horizontal trench.

waste saturation and impact area.

The results of the modeling efforts for the horizontal trench are presented in Figure 7-2 where the distance from the trench reached by reintroduced leachate as a function of the flow rate per unit length of trench is plotted. As can be seen in Figure 7-2, the impact distance increases as flow rate increases. The simulation was conducted assuming a waste hydraulic conductivity of 10 cm/sec. Influence distance may be somewhat lower at lower hydraulic conductivities. Influence distance also appears to increase when intermittent leachate introduction is practiced. The influence distances in Figure 7-2 should be used as guideline particularly when placing horizontal trenches near the landfill surface and boundaries.

The saturation isoclines provided by the model (see Appendix C) suggested that flow rates above 6.0 m^3/day/m trench result in the upward propagation of a saturated front and artesian conditions at the landfill surface. The degree of saturation isoclines for the horizontal trench indicate that insufficient spacing of trenches or over-pumping can result in vertical leachate seeps, and possibly artesian conditions. From these results, it is apparent that injection lines should be conservatively distanced from the landfill surface, boundaries, and each other.

Townsend (1994) recommended at least three m of waste placed on top of a horizontal injection line and a distance of at least 6m from side slopes to avoid seeps and artesian conditions when pumping approximately 1.22 m^3/day/m of trench at 55 kPa. Miller, et al (1993) also selected a six-m spacing for trenches based on results of excavation studies at a recirculating cell operated by the DSWA.

Intermittent introduction, permitting a fill and drain operation can also prevent saturated conditions from developing. French drains may be necessary at landfill slopes to control side seeps.

Saturation profiles for the vertical well (see Appendix C) suggest that the leachate will initially show preferential flow vertically along the well surface. Such flow may contribute to the localized subsidence around the wells at full-scale sites. Higher saturations (greater than 0.6) initially develop along the well surface and slowly begin to propagate laterally and vertically as leachate attempts to percolate downward more quickly than it can be conveyed by the waste matrix. Modeling found that the impact area was, like the horizontal trench, a function of the rate of flow, however in this case small increases in flow resulted in large increases in impact area. Vertical well spacing is conventionally 35 to 100 m (118 to 333 ft).

As seen in Appendix C, the vertical well is inefficient at wetting the upper portion of the landfill while the horizontal trench is less effective at wetting the lower portion of the fill, except at high flow rates. A combined system would then deliver the most uniform wetting of the waste with the well impacting the lower portion and the trench impacting the upper portion. Alternative placement of layers of trenches at right angles to each other at each lift may also increase impact area. Use of low permeable material, such as gravel, extending from the vertical wells to serve as wicks are being used at several landfills to increase the impact area.

Thus the design of a recirculation system should involve more than one recirculation system. Initial wetting with leachate as the waste is placed is also recommended. Once sufficient waste is in place (3 to 6 m (10 to 18 ft)), horizontal trenches and vertical wells can be utilized. Trench spacing can be determined using the following procedure involving Figure 7-2.

1. Determine desired volume to be recirculated using hydrologic modeling results (*i.e.* HELP).
2. Determine dimensions of the landfill.
3. Select length of trenches.
4. Determine the flow rate per length of trench.
5. Determine the spacing of the trench.

If flow is below the curve on Figure 7-2, leachate should be pumped to the trench during portions of the day and rotated from trench to trench to increase flow to each trench. Low flow rates will result in incomplete wetting of the landfill. If the flow is above the curve on Figure 7-2, the spacing of the trenches should be reduced. Note that the influence distance should be doubled to determine trench spacing requirements.

As an example, consider a 2-ha (five-acre) landfill cell recirculating an average of 15 m^3/ha/day. The landfill is 300 m by 67 m and the perforated section of the trenches will be 50 m long. Leachate will be pumped to each trench for four hours each day, resulting in a flow rate of 3.6 m^3/hr/m. The influence distance is therefore three m, from Figure 7-2, and the trenches should be spaced six m apart for a total of 50 trenches.

Final and Intermediate Caps

The typical landfill today is closed within two to five years, and, because of high construction costs, is often built to depths of well over 100 m (300 ft). Once the landfill reaches design height, a final cap is placed to minimize infiltration of rainwater, minimize dispersal of wastes, accommodate subsidence, and facilitate long-term maintenance. The cap may consist (from top to bottom) of vegetation and supporting soil, a filter and drainage layer, a hydraulic barrier, foundation for the hydraulic barrier, and a gas control layer.

The rapid closure and deep construction of the modern landfill tends to minimize surface exposed to infiltration. In addition, many states prohibit the disposal of yard waste in landfills, eliminating an important 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 still be below optimum levels for biological degradation (Leszkiewicz and McAulay, 1995). In reality, a significant fraction 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. These factors contribute to dry-tombing and storage of waste as opposed to rapid stabilization promoted by the bioreactor approach.

Subtitle D of RCRA requires provision of a final cap which will **prevent** the infiltration of precipitation. Postponement of final RCRA closure should be considered in lieu of an intermediate cap (composed of more permeable soil) which provides for limited infiltration of moisture, along with leachate recirculation, to maintain appropriate conditions for biodegradation of waste. The intermediate cap has advantages related to subsidence accommodation as well. Subsidence is discussed further in Chapter 8. Provision of an intermediate cap may require more confidence in the bioreactor landfill prior to acceptance by regulators.

Gas Collection

As discussed in Chapter 6, several laboratory and pilot-scale lysimeters have documented increased gas production rates and total yields as a result of moisture addition (Pohland, 1975; Pohland, et al, 1992; Buivid, et al, 1981). Limited data also suggest that, as in lysimeters, gas production at larger sites is significantly enhanced over traditional landfilling and gas collection practices as a result of both accelerated waste stabilization as well as the return of organic material in the leachate to the landfill for conversion to gas (as opposed to washout in conventional landfills). Gas production enhancement can have positive implications for energy production and environmental impact, however, 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. Captured gas in turn must be utilized in a manner which controls the release of methane and nonmethane organic compounds and provides for beneficial offset of fossil fuel use.

Horizontal collection systems are gaining in popularity as an efficient method of gas extraction for active landfills and, in particular, for bioreactor landfills. The gas extraction trench is constructed in a similar manner to the horizontal injection trench for recirculation; trench excavation, backfilling with gravel, and placement of a perforated pipe. In fact, in the case of Alachua County, Florida, horizontal leachate injection pipes are also being used to extract gas (Miller, et al, 1994). Use of leachate introduction devices for gas collection is being considered at many landfills and is most promising, despite problems associated with two-phase countercurrent fluid flow. Horizontal spacing of extraction trenches ranges from 30 to 120 m (100 to 400 ft); vertical spacing ranges from 2.5 to 18 m (8 to 60 ft) or one trench for every one or two lifts of waste. Trench construction should consider the overburden of continued filling and the effects of compactors moving over the trench.

A recent study investigated the economics of active landfill management with respect to gas utilization (Lewis, 1995). Three management alternatives were investigated; conventional single-pass leachate operation, bioreactor technology for gas production enhancement, and triggered operation. Triggering employs methods to control the timing of the onset of landfill gas generation such as temperature management, moisture, and nutrient management (Augenstein, et al, 1993). With such control, the majority of gas could be generated following landfill closure and the installation of the gas collection system. While triggering is not yet practical at full-scale it is certainly a desirable outcome of current research efforts.

Bioreactor landfills were found to have advantages of increased waste stabilization and landfill gas production over a shorter period of time. However, if landfill gas is not collected immediately, much of the advantages of energy recovery are lost, and associated safety and environmental risk escalates. In addition, the rapid increase and decline in gas generation associated with bioreactor operation may make it difficult to match gas utilization with gas collection, particularly when using constant capacity alternatives and alternatives requiring expensive cleanup such as electric power or vehicular fuel generation. Thus, much of the gas collected during peak production periods may be wasted. Staging of construction of gas utilization equipment over time may be possible, but only if justified by sustained net revenue over an extended project life. As discussed above, use of horizontal collection systems prior to landfill closure was found to have significant economic benefit over less efficient collection systems when used to extract gas generated by bioreactor landfills. Triggering of gas production was found to have significant economic benefit when compared to conventional operation.

Cell Construction

For economic reasons, the recent trend in landfill construction is to build deep cells to provide a life of two to five years, for economic reasons. 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 separated cells are easier to isolate to minimize stormwater contamination and shed water more efficiently when covered. Baetz and Byer (1989) calculated that as much as 30 percent more leachate is generated from horizontal cell construction as compared with extreme vertical construction with minimal face exposure. Once closed, methanogenic conditions within the cell are optimized and gas production and collection is facilitated. It may also be possible to then use the closed cell to treat leachate from new cells as discussed in more detail in Chapter 8. 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.

Summary

The design of the bioreactor landfill is still an evolving concept, however, there are several features described in this chapter which appear to be essential to the proper utilization of this technology. Many of these features are depicted in Figure 7-3 and are summarized below:

- minimum of a single composite liner comprised of compacted soil and a geomembrane,
- a conservatively designed leachate collection system which will accommodate recirculated flows,
- an appropriately designed drainage and filter system to minimize clogging and head on the liner,
- adequate storage external to the landfill to accommodate storm flow and to provide sufficient flow to continue to recirculate between storm events,
- daily cover which does not affect the passage of moisture through the landfill,
- a small, deep cell active for two to five years,
- a leachate recirculation system which effectively wets the landfill contents, but does not produce side seeps or surface flows, and is compatible with the landfill cap,
- an active gas collection system which captures and controls gas emissions throughout the life of the landfill, and,
- a landfill cover that can maintain integrity as the landfill volume decreases.

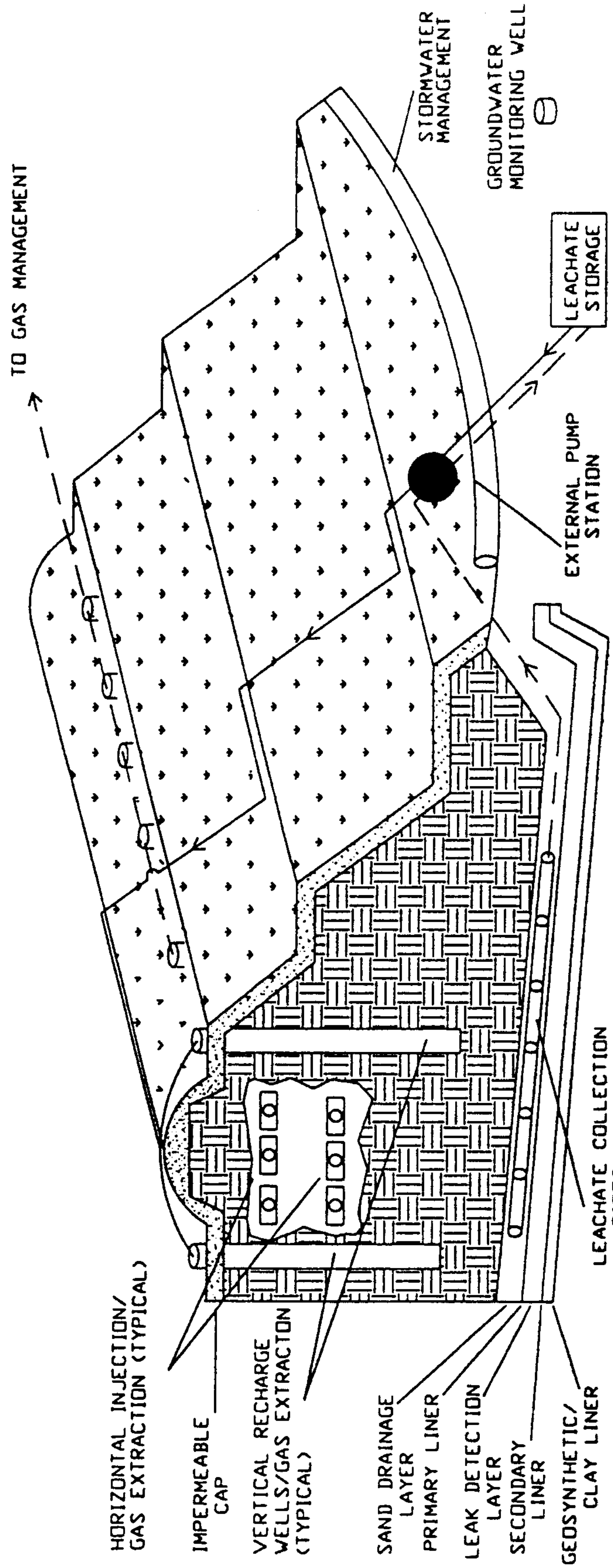

Figure 7-3. Schematic diagram of leachate recirculating landfill.