Chapter 8
Landfill Bioreactor Operation

Introduction
To successfully operate the bioreactor landfill, it is necessary to implement a variety of control mechanisms. This chapter provides a description of pertinent control mechanisms and recommendations for their full-scale application.

Waste Characterization
MSW composition affects leachate quality, landfill gas composition and quality, waste degradation rates, and resource recovery potential. Composition is a function of characteristics of the generating population. For example, during the period from 1972 to 1987, the population in the United States increased by 16 percent. During that same period, however, MSW discards increased by 28 percent. This increase may be explained by, among other facts, the 34 percent jump in the number of households (due to divorces, elderly population, and later marriages) which resulted in increases in yard waste and discarded appliances, home furnishings, and clothing. In addition, the work force increased by 38 percent (office employment increased by 72 percent) leading to more paper waste and a change in lifestyle which led to use of convenience foods producing more packaging waste and less food waste (Rattray, 1993). More recently a decline in per capita waste generation has been noted as well as a reduction in the percentage of waste which is placed in landfills as a result of increased source reduction and recycling (Franklin and Associates, 1994).

Variations in waste characteristics must be considered as future landfills are designed and operated. Composition changes in response to new regulations and population characteristics must be foreseen and accommodated. The Office of Technology Assessment has identified as a high priority the need to reduce MSW generation rates and toxicity (U.S. Congress, 1990). Such a reduction will help to minimize waste management costs, improve the efficiency of the use of natural resources, generate public confidence in governmental MSW policies, and enhance the quality of landfill leachate and gas. Many states are precluding yard wastes from lined landfills, eliminating a source of moisture, nitrogen, and organisms capable of degrading waste. The impact of these changes on bioreactor operation is difficult to predict.

Preprocessing of wastes does permit some control of MSW characteristics. Separation of inert and organic waste, bag opening, shredding, and household hazardous waste removal provides for a more uniform waste, improve leachate and gas quality, equalizes subsidence (facilitating post-closure care), and simplifies landfill operations.

Physical properties of MSW provide some opportunity for reactor control. These properties chiefly include in-place density and particle size and primarily influence moisture routing within the landfill. In-place density can be controlled by compaction in the field or by baling of wastes prior to landfilling. Field compaction is accomplished by moving heavy equipment over the wastes a number of times. Density increases with the number of passes (three or four is optimal) and decreases with the thickness of the lift. Typical densities vary from 475 to 830 kg/m^3 (800 to 1400 lb/yd^3). Baling can increase density to as high as 890 kg/m^3 (1500 lb/yd^3). Greater compaction (and resulting greater density) has advantages associated with more efficient use of air space, reduced settlement, and reduced cover material requirements. However, hydraulic conductivity is diminished, moisture distribution is impaired, and leachate short circuiting is promoted; therefore leachate may be relatively weak in strength, but waste degradation may be delayed. Successful bioreactor operation requires reduced compaction to promote even leachate distribution. However, increased settlement rates can be expected under these circumstances.

Particle size can be reduced through shredding prior to waste placement. Unless particle size is reduced to sub-micron diameters, however, shredding cannot overcome mass transfer limitations of degradation, particularly in a dry landfill (Noble and Arnold, 1989). Shredding does promote a more uniform waste and reduces fire potential, blowing wastes, and the need for daily cover. Shredding also improves water distribution and provides more even settlement. In addition, more waste is exposed to microbial activity and consequently biodegradation may be enhanced. Dewalle, et al, (1978) found that shredding significantly increased gas production and concluded that approximately 50 percent of potentially degradable organic material is protected in a landfill without shredding. Bookter and Ham (1982) also concluded that shredding increased the rate of decomposition in test cells, as did Otieno (1989). However Tittlebuam (1982) found shredding had no effect on degradation in laboratory-scale lysimeters. Reinhardt and Ham (1974) reported an additional 27 percent in density for milled refuse at equivalent compaction as compared with nonshredded waste. Leachate from shredded waste was more highly contaminated during early stages and less contaminated during later phases. Reinhardt and Ham concluded that leachate flowed more evenly in milled refuse. Shredding adds significant cost to landfill operations and is more frequently used to facilitate resource recovery and combustion, however, if used judiciously, shredding may provide sufficient advantages in terms of enhanced gas production and minimized long-term liability to justify the cost.

Oxidation-Reduction Conditions

Oxidation-reduction (redox) conditions within the landfill establish waste degradation pathways. High redox potential associated with aerobic conditions provided for accelerated waste stabilization and reportedly improved leachate quality (Stegmann and Spendlin, 1990). Aerobic landfilling is more akin to today's composting operations and has been promoted by many investigators since the 1960's (Merz and Stone, 1970). However, the presence of air in a landfill may create fire potential, has additional operating costs associated with provision of air, and may produce off-gases which require collection and treatment. Anaerobic degradation, however, leads to the production of methane which can be recovered for energy generation. In addition, anaerobic degradation pathways are available for many compounds which are not amenable to aerobic degradation (for example chlorinated aliphatic hydrocarbons).

Aerobic conditions have been encouraged in studies in West Germany using thin layer (less than 0.4 m) compaction (Stegmann and Spendlin, 1990). Thin layer compaction was found to provide increased and more uniform waste density, improved water distribution, and enhanced penetration of air. The biological process was then accelerated, with easily degraded organic materials removed prior to the onset of anaerobic conditions, thus limiting the production of organic acids which can retard methanogenesis. Thin-layer compaction was discussed in more detail in Chapter 2.

Studies in the United Kingdom have investigated air injection into completed landfills (using vertical gas wells), in order to promote aerobic degradation (Fletcher, 1989). Because of the energetics of aerobic metabolism, temperature temporarily increased locally (by 17°C) and dramatically stimulated subsequent anaerobic activity as evidenced by increased gas production.

Pilot studies in Sweden have investigated two-step degradation within landfills, whereby acidogenic conditions are maintained in one portion of the landfill, and methanogenic conditions elsewhere. The high strength, low pH leachate produced within the acid phase area was recirculated to the methane producing area for treatment. Consequently, methane production can be accomplished under controlled conditions in an area suitably designed for maximum methane recovery (Lagerkvist, 1991a).

Moisture Content

Moisture addition has been demonstrated repeatedly to have a stimulating effect on methanogenesis (Barlaz, et al, 1990), although some researchers indicate that it is the movement of moisture through the waste as much as it is water addition that is important (Klink and Ham, 1982). Moisture within the landfill serves as a reactant in the hydrolysis reactions, transports nutrients and enzymes, dissolves metabolites, provides pH buffering, dilutes inhibitory compounds, exposes surface area to microbial attack, and controls microbial cell swelling (Noble and Arnold, 1989).

Leachate recirculation appears to be the most effective method to increase moisture content in a controlled fashion. The advantages of leachate recirculation include positive control of moisture content, leachate treatment, and liquid storage and evaporation opportunities. Pohland, (1975) suggested that leachate recirculation could reduce the time required for landfill stabilization from several decades to two to three years. Suflita, et al (1992) and Miller, et al (1994) both noted the important role of moisture in supporting methanogenic fermentation of solid waste when examining samples removed from operating landfills. Recommended moisture content reported in the literature ranges from a minimum of 25 percent (wet basis) to optimum levels of 40 to 70 percent (Barlaz, et al, 1990). During lysimeter studies of the effect of moisture content on waste degradation, Otieno (1989) observed that complete saturation was not conducive to methanogenesis. Negative impacts of saturation may be due to poor circulation of leachate and the accumulation of VOAs and lead to side seeps.

Increased moisture content also permits significant storage of moisture within the fill. Rovers and Farquhar (1973) determined refuse moisture retention to be between 10 and 14 percent of dry waste by volume above initial waste moisture. A simple analysis of in situ storage can be done given incoming waste tonnage and precipitation data. For example, assume waste receipts average 272 metric tons/day (300 ton/day), annual average infiltration is 0.76 m (30 in), and waste is placed at a specific weight of 593 kg/m^3 (1000 lb/yd^3). If this waste has a moisture holding capacity of 15 percent by weight (or 0.25 m^3/metric ton (60 gal per ton)), a total of 68 m^3/day (18,000 gal/day) of moisture can be absorbed. Consequently, an open area of approximately 3.3 ha (8.0 acres) can be supported by leachate recirculation without ex situ storage or treatment. Ex situ storage will still be required to deal with peak storm events which occur while the landfill is open, as well as to manage leachate recirculated about closed cells. Storage was treated in more detail in Chapter 7.

Recirculation Strategies

The practice of leachate recirculation must balance two processes, the biological processes controlling waste degradation and the hydrologic capacity of the waste (the rate at which leachate moves through the waste) controlled by the waste permeability. Frequency of leachate recirculation, on a practical basis, has historically been dictated by the inventory of accumulated leachate. Operators more or less have sought a place to put large volumes of water. Such practice can lead to saturation, ponding, and acid-stuck conditions, particularly during early degradation phases. Unfortunately, the level of knowledge of bioreactor operations is still fairly limited, particularly at field-scale, however some guidance can be obtained from related studies of anaerobic digestion.

The biological processes occurring in the landfill are largely anaerobic, as described in Chapter 6. These processes are fairly sensitive to environmental conditions such as pH, temperature, toxic compounds, and the presence of oxygen. These factors are discussed in more detail in later sections of this Chapter. Control of the processes in a landfill is similar to that required for an anaerobic digester, however, since a digester is typically a well-mixed, external reactor, control of the digester is much easier to accomplish. Landfill process control can be achieved to some degree by controlling the rate at which moisture is introduced. It is extremely important to introduce leachate slowly prior to the onset methanogenesis, while monitoring gas and leachate quality. High flow rates will deplete buffering capacity and remove methanogens. The presence of methane suggests that methanogenesis is occurring. Leachate should be monitored for pH and, more importantly, VOAs and alkalinity. Acid stuck conditions are indicated by a high VOA to alkalinity ratio (greater than 0.25) suggesting low buffering capacity. pH may still be in an optimum range at this point, however the process may be heading for problems.

A procedure employed at several successful operations is to rotate moisture introduction from one area to another, allowing areas to rest between recirculation episodes. This facilitates gas movement and minimizes saturation which is particularly important during the early phases of the degradation process (Leckie, et al, 1979, Rees, 1980). Saturation may be indicative of stagnant conditions, which have been shown to be detrimental to the landfill process.

Leachate recirculation should be initiated as soon as possible following waste placement (once sufficient waste is present to absorb the recirculated liquid, perhaps following placement of the first lift) to ensure proper moisture content for biodegradation. Doedens and Cord-Landwher (1989) observed that leachate recirculation initiated at the commencement of operations at full-scale landfills resulted in a more rapid reduction in leachate organic strength than for landfills where recirculation was delayed for up to four years.

Once gas production is well established, leachate can be recirculated more frequently and at greater flow rates. At this point, the rate of introduction of leachate is controlled by the moisture capacity of the waste which, because we are largely dealing with vertical flow, is a function of the permeability of the waste. Many researchers have investigated the hydraulic conductivity of landfills. The results of their investigations are summarized in Table 8-1, where values are seen to range from $10^{-5.9}$ to 10^{-2} cm/sec. In many cases, reported hydraulic conductivities are erroneously high because of measurement techniques (pump tests) which include a horizontal flow component. Several researchers have found that hydraulic conductivity decreases as waste density increases (Fungaroli and Steiner, 1979 and Bleiker, et al, 1993). Hydraulic conductivity is a function of the degree of saturation. Korfiatis, et al (1984) developed power equations which describe the relationship between hydraulic conductivity and degree of saturation (see Appendix C). This relationship shows that hydraulic conductivity declines with a lower degree of saturation. Bleiker, et al (1993), found that hydraulic conductivity decreases with depth as well due to the impact of overburden on density. Values as low as 10^{-7} cm/sec were measured at approximately 30 m of landfill depth. This behavior contributes to saturated conditions (leachate mounding) frequently found near the bottom of the landfill. Hydraulic conductivity also declines over time as a result of chemical precipitation and biological clogging. The impact of long-term bioreactor operation on conductivity is not known.

To optimize the rate of flow through the landfill as well as the impact area, short term high-rate leachate introduction may be best during early phases of operation. In this way, saturated conditions can be achieved in areas immediately surrounding the recirculation device, lower back pressure will be encountered, and greater areas of the landfill will be wetted. Calculations can be made based on expected hydraulic conductivity, impact area (from Figure 7-2), and desired depth of wetting. For example if a 50-m horizontal trench is used with a spacing of 5 m, corresponding with a flow rate of 250 m^3/d, the area should be wetted within 6 days. That trench can be abandoned for several weeks and the next trench utilized. Once methane formation commences, the trench can be used more or less as necessary, while watching for side or surface seeps.

To maximize waste stabilization, leachate should be recirculated to all parts of the landfill, if possible. Uniform distribution is extremely difficult to achieve, however, and may best be accomplished through prewetting of waste as it is placed in the fill. Non-uniform distribution may have been the biggest problem with early recirculation attempts, leading to short circuiting, ponding, side-seeps, and interference with gas collection. Ideally, minimal compaction should be practiced for the landfill bioreactor to optimize early leachate recirculation. With time, density will increase and conductivity will decline, however at that point the landfill cell will be completed and minimal recirculation will be necessary. A large amount of settlement will occur under this scenario and should be anticipated in plans for routine surface maintenance.

Table 8-1. Refuse Hydraulic Conductivity

Reference	Hydraulic Conductivity, cm/sec	Experimental Details
Fungaroli and Steiner, 1979	10^{-3} to $10^{-1.7}$	Lysimeter, pumping tests, milled waste, 90 - 300 kg/m^3
Korfiatis, et al, 1984	$10^{-2.5}$ to $10^{-2.3}$	laboratory pump tests
Oweis and Khera, 1986	$10^{-1.8}$ to $10^{-3.2}$	Field pump tests, 574 to 1140 kg/m^3
Wehran, Engr., 1987	$10^{-2.8}$ to $10^{-2.2}$	4-in PVC permeameter installed in test cells
Oweis, et al, 1990	$10^{-3.8}$ to 10^{-3}	In situ draw down tests, pump test, test pit infiltration
Bleiker, et al, 1993	$10^{-4.4}$ to 10^{-7}	falling head permeameter tests
Townsend, 1994	10^{-6}	Zaslovshy's wetting-front infiltration equation applied to infiltration pond

When 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). As described in a previous section, 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 in another part.

Effects of Waste Placement Rate

A mathematical model was developed to examine the impact of key operating parameters on leachate quality (specifically COD at present, although the model could be modified to accept any quality parameter). The model is based on a mass balance about one or more leachate recirculating landfill cells and utilizes data presented in Chapter 6 which describe the rate at which leachate COD increases and decreases. Model assumptions and details are provided in Appendix D. Site specific operating criteria can be used as input to the model to evaluate expected leachate quality. The model was successfully validated using data from a recirculating cell operated by the DSWA (Agora, 1995).

The model was used to investigate the impact of waste placement rate on leachate COD. Waste placement rate was varied from 20 to 70 metric TPD placed in a landfill 50 m by 50 m by 12 m deep. All other parameters were kept constant. Waste density was assumed to be 600 kg/m^3, void volume 0.4, infiltration rate was 1.5 m^3/day, 95 percent of leachate generated was recirculated, initial leachate COD was 6,000 mg/l, and the cell was 75 percent saturated. Waste was assumed to undergo hydrolysis/acidogenesis for 400 days during which the COD rate of increase was 0.004 day^{-1}. After 400 days, methanogenesis begins and the rate of decrease in leachate COD was 0.001 day^{-1}.

The predicted leachate quality as a function of waste placement rate is shown in Figure 8-1. At lower waste placement rates, the leachate COD concentration peak is higher and COD declines at a lower rate. Also the lower the waste placement rate, the earlier the COD peak occurs. At higher placement rates, the cell is filled faster and the shift from acidogenesis/hydrolysis (which contributes to high COD) to methanogenesis occurs more uniformly throughout the cell. Thus the rapidly filled cell behaves more like laboratory-scale reactors which are filled almost instantaneously and tend to have sharper COD peaks. The slowly filled cells tend to prolong the high COD, acidic phase.

Use of Old Cells

The present design of the MSW landfill generally calls for a series of hydraulically separated cells which are opened and closed sequentially. Active landfills in most parts of the US generate relatively large volumes of leachate which tend to become increasingly contaminated as waste is emplaced. Leachate recirculation at this time is important to ensure that the waste reaches moisture levels near field capacity. With the provision of appropriate operational controls which include leachate recirculation, the landfill, once closed, can function as a bioreactor, providing in situ treatment of organic fractions of the waste as well as recirculated leachate. Within a short period of time the quality of the leachate will improve and gas production rates will reach peak values.

As the next cell is opened, leachate volume and strength will increase once again. However, leachate produced from this cell can be recirculated to both the closed cell and the active cell, providing in situ treatment of the leachate and moisture control for the active cell as depicted in Figures 8-2 through 8-4. Although leachate organic strength will rise and fall with each reactor opening and closing, the magnitude of each subsequent cycle should be dampened as a result of the in situ treatment provided by the closed cells. This phenomenon has been observed at the full-scale Lycoming County Landfill which has practiced leachate recirculation since the mid 1970's (Natale and Anderson, 1985) and investigated using laboratory-scale lysimeters by Doedens and Cord-Landwher (1989). At present, however, RCRA Subtitle D precludes the introduction of non-indigent leachate into older cells.

The mathematical model described in the above section (see Appendix D) was also utilized to

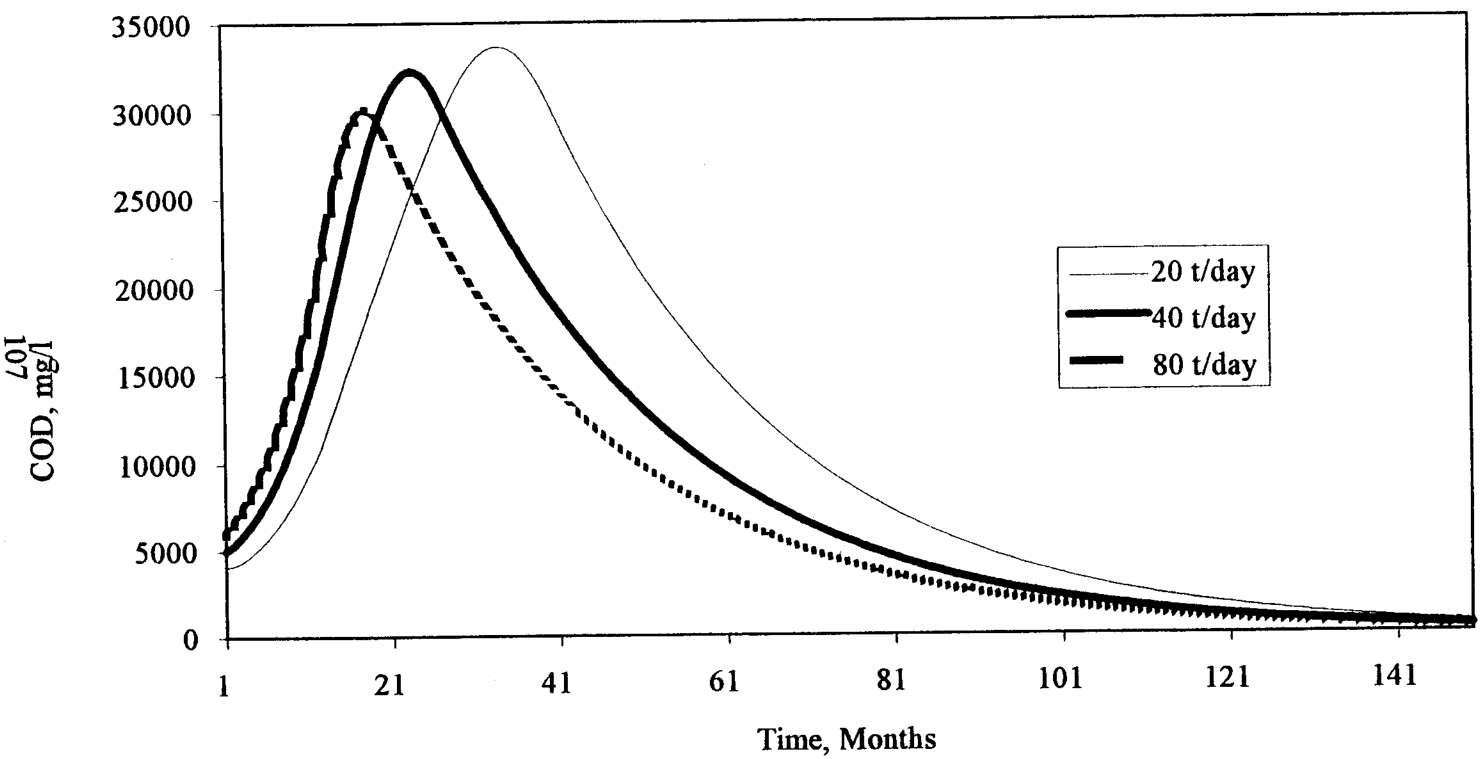

Figure 8-1. Effect of waste placement rate on leachate quality.

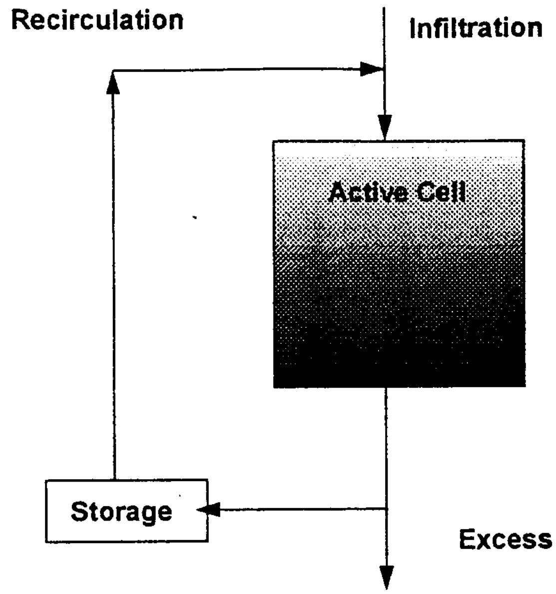

Figure 8-2. Leachate recirculation scenario - single cell.

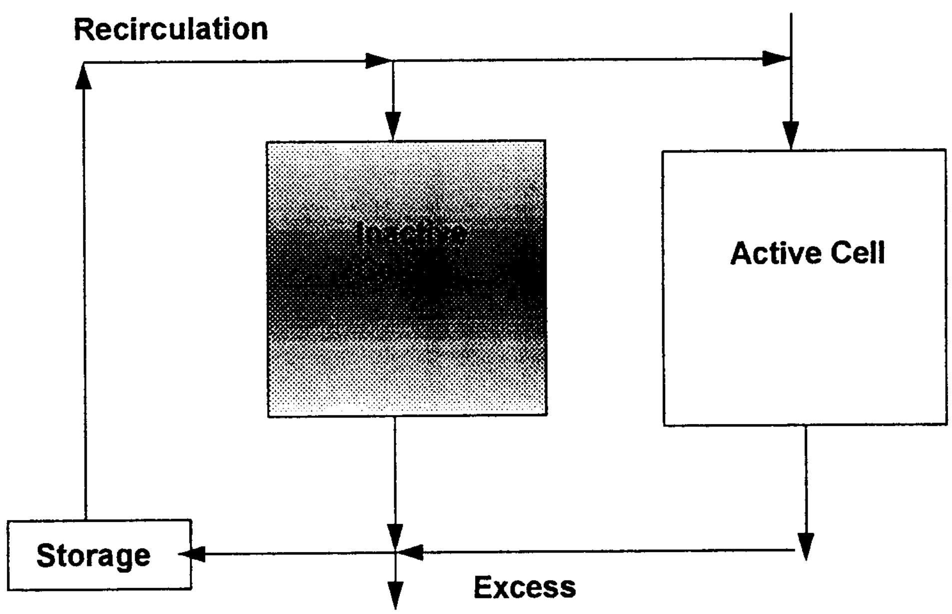

Figure 8-3. Leachate recirculation scenario- two cell sequencing.

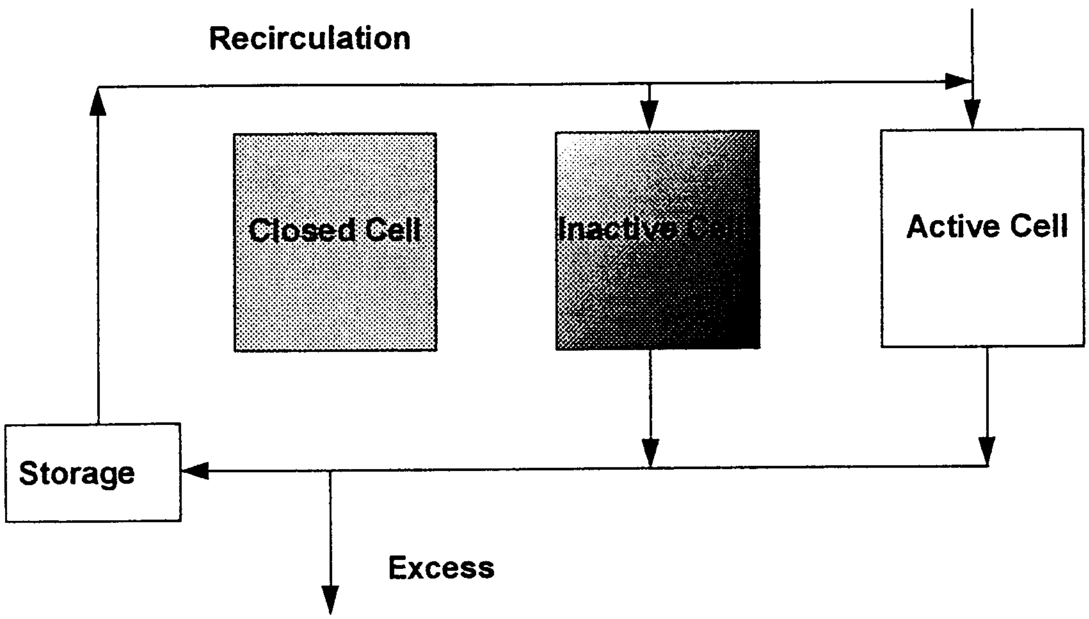

Figure 8-4. Leachate recirculation scenario - closed cell.

evaluate the effect of sequential cell recirculation. Two cells were modeled with input parameters as described above. A 95 percent leachate recirculation rate was used. All of the leachate generated by the active cell was recirculated to the inactive cell. The COD output from both a single cell and the two cell configuration is plotted in Figure 8-5. Leachate recirculation over the inactive cell makes a drastic difference in leachate quality due to the attenuation of leachate organic strength by the fully established methanogenesis phase of the inactive cell. Two-stage leachate recirculation can also be achieved through composting or aerobic pre-stabilization of bottom layers of waste in order to treat leachate generated in the top layers of the landfill as it passes through the bottom layers. Clearly, use of this leachate management option should be further evaluated at field scale.

Bioreactor Augmentation

The consortium of microorganisms involved in the stabilization of waste has specific environmental requirements including, among others, pH, temperature, and micro- and macro-nutrients. With the multitude of factors influencing landfill processes, it has been difficult to evaluate, full scale, the impact of any one variable. Laboratory studies have investigated many of these environmental parameters and the results, described in following sections, can be helpful in determining which elements might be important to control. Field studies are in progress to obtain more insight into full-scale landfill effects.

Temperature Control
Because waste degradation involves biochemical reactions, the rate of degradation tends to increase with temperature. The temperature within a landfill is determined by a balance between heat production during the biological degradation of organic waste fractions and the loss of heat to the surrounding soil and atmosphere (Rees, 1980, Hartz, et al, 1982). The microbial processes are capable of significant heat generation, particularly at higher moisture conditions. Optimum temperature has been reported to be 40°C by Gurijala, et al ,1993 and 34 to 38°C by Mata Alvarez and Martina-Verdure (1986) with significant inhibition observed at temperatures above 50 to 55°C (Pacey, 1987). Temperature control at full-scale landfills may be difficult to economically achieve. As previously discussed, introduction of air and the consequential onset of aerobic activity serves to rapidly increase temperature and has been found to stimulate methane production. Another potential method of temperature control under investigation is the heating of recirculated leachate such as used in Sweden's experimental "Energy Loaf" (Brundin, 1991). At this point in time, the use of temperature to control the landfill bioreactor is not practical and its benefits not thoroughly demonstrated, therefore it is not recommended.

Nutrients
Nutrient requirements are generally met by the waste at least during early degradation phases (Barlaz, et al, 1990), although phosphorous may be limiting during later stages (Pohland, 1975). During methane potential testing of samples retrieved from a DSWA landfill, Pohland (1992) found that the addition of nitrogen and phosphorous to mature samples stimulated methane production. Tittlebaum (1982) added nutrients to laboratory-scale lysimeters and reported no effect on degradation rates. Mata-Alvarez and Martinez-Verdure (1986) indicated that laboratory-scale MSW digesters achieved 90 percent degradation of biodegradable material within 27 days without nutrient addition, provided other environmental factors were within optimal ranges. Nutrient addition adds to the complexity of operation and does not appear to offer sufficient advantages during active landfill phases to warrant use.

Buffering
Optimum pH for methanogens is approximately 6.8 to 7.4. Buffering of leachate in order to maintain pH in that range has been found to improve gas production in laboratory and pilot studies (Fletcher, 1989, Pohland, 1975, Pohland, 1980, Tittlebaum, 1982, Leuschner, 1989). Gurijala, et al, (1993) examined samples removed for the Fresh Kills Landfill in New York City for methane potential and found no methane production outside of this range. Buffering as a control option may be best used in response to changes in leachate characteristics (*i.e*, a drop in pH or increase in VOA concentration) in conjunction with leachate recirculation (Stegmann and Spendlin, 1989). Particular attention to pH and buffering needs should be given during early stages of leachate recirculation when excessive moisture can lead to an accumulation of acids, low pH, and inhibition of methanogens. Careful operation of the landfill bioreactor initially through slow introduction of leachate should minimize the need for buffering. Provision for interim lime or sodium hydroxide addition and mixing at leachate

storage should be considered.

Inoculation

Seeding or inoculating the landfill has been investigated, usually through the addition of wastewater treatment facility sludges. In laboratory and pilot studies, sludge addition has had mixed impact on degradation (Barlaz, et al, 1990). ten Brummeler, et al (1991), however, found that composted sludge had a positive effect on the start up of MSW digestion, preventing souring experienced in reactors with leachate recirculation alone. Studies by Leuschner (1989), Pohland (1992) and NYSERDA (1987) all showed positive effects of addition of sludge on methane generation onset and rates. Stegmann and Spendlin (1989) indicated that sludge addition does not enhance gas production. Leckie (1987) found that the addition of septic tank pumpings stimulated acid fermentation and suppressed methane generation. Any effect measured may be due to buffering or moisture addition more than seeding. In most cases, however, operators prefer to exclude sludge because it is difficult to work with at the waste face.

Composted waste offers an alternative source of seed. Studies in West Germany found that old refuse was superior to sludge in stimulating methanogenesis (Stegmann and Spendlin, 1989). The addition of a lift of new waste on top of 1.5 m of five-year old waste also demonstrated the ability of stable waste to treat new leachate (Bookter and Ham, 1982).

Daily and Intermediate Covers

As moisture moves through the landfill, waste heterogeneity in permeability will be frequently encountered, 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 and Maris, 1982). Accumulations within the site to depths of 1.2 m (48 in) or more were reported due to the use of low permeability soil cover. Natale and 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. Lechner, et al (1993) observed ponding within the Breitnau test cells and attributed it to calcium deposition. Exhuming portions of a recirculating cell operated by the DSWA revealed perched water within the landfill as a result of layers of material which prevented moisture movement (Miller, et al 1993). Dry areas beneath perched water showed almost no degradation.

In order to minimize ponding and horizontal movement, use of high permeability soils and/or alternative daily cover should be considered. Alternative daily cover materials include mulched or composted yard waste, foam, carpet, and geotextiles. Geotextiles and carpet covers may be removed prior to the next addition of waste, while foam quickly dissipates when waste is placed. In either case, the flow of moisture is not impeded by these materials. Analysis shows that alternative daily cover can be cost-competitive with natural soils.

Settlement
Another consequence of bioreactor operation is enhanced settlement rates. Settlement is caused by the following factors (McBean, et al, 1995):

- reduction in voids space and compression of loose materials due to overburden weight,
- volume changes due to biological and chemical reactions,
- dissolution of waste matter by leachate,
- movement of smaller particles into larger voids, and
- settlement of underlying soils.

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, CA pilot-scale landfills, the leachate recirculated cell settled by as much as 20 percent of its waste depth, while dry cells settled less than 8 percent (Leckie, et al, 1979). Wet cells at the Mountain View Landfill, CA settled approximately 13 to 15 percent, while control dry cells settled only 8 to 12 percent over a four year period (Buivid, et al, 1981). Wetting of waste as it is placed has been practiced 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 long-term final cover maintenance can be reduced as well. One potential problem with enhanced settling is the impact on leachate reintroduction and gas collection piping. Appropriate use of flexible leachate feed connections to trenches and wells is recommended to prevent pipe breaks.

Settlement may also negatively impact the integrity of internal leachate recirculation devices. Vertical wells may experience displacement due to waste shifting. Trenches will experience variable settling rates and consequently pipe breakage and low spots may occur. In these cases leachate distribution may be uneven. Some designers have recommended telescoping vertical piping to accommodate settling, however this approach does not accommodate horizontal shifting. It is anticipated that use of sufficiently permeable trench backfill will provide continued service even if pipes break, clog, or settle. Therefore, great care should be taken in selecting and placing backfill material. It may be necessary to retrofit the landfill with surface infiltrators and vertical wells after the majority of settlement has occurred, perhaps in conjunction with final closure construction. Again, more information is needed to evaluate the long-term survivability of recirculation devices.

Monitoring
Landfill monitoring is important from a regulatory, operating, and design perspective. Use of the landfill as a bioreactor necessitates additional monitoring efforts because it is still considered innovative and because monitoring facilitates control of the process. Augenstein (1995) recommends monitoring of gas recovery and composition, waste characteristics, leachate flow and composition,

liner integrity, and waste settlement. Table 8-2 provides recommendation for bioreactor process performance monitoring. McBean, et al (1995) provided a more general monitoring program for landfill operation.

Measurement of gas flow rate can be particularly troublesome because of high moisture and contamination. A number of instruments are available including the pitot tube, orifice, venturi, vortex shedding, and thermal dispersion meters. An excellent review of available gas meters is provided by Campbell, (1991).

Waste characteristics are also difficult to assess in situ. Soil type moisture sensors (gypsum blocks) have been used in several installations recently to provide continuous moisture monitoring, however it is too early to conclude on their effectiveness. It is expected that gypsum blocks will have a short life due to leachate attack and may be most useful in indicating moisture arrival rather that exact moisture content. Pressure transducers placed on the liner have also been used to monitor hydrostatic head. Other important waste and leachate analyses include cellulose, lignin, and ash content, biological methane potential, nutrient content, and alkalinity. These parameters can be useful in determining the relative stability of the waste. Sample retrieval is discussed by Miller, et al (1994) using 15-cm (six-inch) augers and Suflita, et al (1992) using a bucket auger.

Leachate characteristics can provide important insight relative to waste degradation phase. Analysis therefore should reflect the expected reactions occurring within the landfill. BOD, COD, pH, TVA, TOC, nutrients, and alkalinity are important early in the life of the cell. COD, metals, ammonia, and conductivity are important at maturity to develop plans for inactivating the landfill and treating remaining leachate.

When is the Waste Stable?

Once waste stabilization has been satisfactorily achieved, the cell should be deactivated by discontinuing leachate recirculation and removing all liquid. The liquid will undoubtedly require some form of physical/chemical treatment to remove remaining recalcitrant organic compounds and inorganic contaminants. The point at which degradation is sufficiently complete to consider the landfill "stable" is not clearly defined. The most appropriate indicators appear to be leachate quality, gas quantity, and waste composition. Consideration of recent pilot-scale testing of leachate recirculation at the Georgia Institute of Technology (Pohland, et al, 1992) offers some insight into this question. In the presence of leachate recirculation, organic strength of leachate as measured by COD, reached a minimum level approximately 1000 days after startup. However, at this time, only 68 percent of the total gas production had occurred. When over 95 percent of the gas had been produced, gas production rates had fallen well below 10 percent of peak rates. Thus it appears from this study that sufficient waste stabilization occurs when gas production reaches relatively low rates (less than 5 percent of peak value) and leachate strength remains low (COD below 1000 mg/l, BOD below 100 mg/l). Other indicators are low leachate BOD\COD ratio (less than 0.1), waste cellulose/lignin ratio less than 0.2 (Bookter and Ham, 1982), low waste biological methane potential (less than 0.045 m^3/kg volatile solids added (Owens and Chynoweth, 1992)), and dark and sludge-like

Table 8-2. Bioreactor Process Performance Monitoring

Parameter	Frequency	Purpose of Monitoring			
		Ex Situ Leachate Treatment	Environmental Impact	In Situ Leachate Treatment	Gas Control
Leachate:					
Organic Strength	Monthly	x	x	x	
Volatile Organic Compounds (VOCs)	Quarterly		x		x
Synthetic Organic Compounds (SOC)	Quarterly		x		
Metals	Quarterly	x	x	x	
Nutrients (phosphorous, ammonia)	Quarterly	x	x	x	
Nonmetal Inorganics (TDS, sulfate, chloride, potassium)	Quarterly	x	x		
Volatile Organic Acids	Monthly	x	x	x	
Flow Rate	Continuous	x		x	
Gas:					
Methane, Carbon Dioxide	Weekly				x
VOCs	Quarterly		x		x
Hydrogen Sulfide	Quarterly		x		x
Flow Rate	Continuously		x		x

Table 8-2. Cont'd.

Parameter	Frequency	Purpose of Monitoring			
		Ex Situ Leachate Treatment	Environmental Impact	In Situ Leachate Treatment	Gas Control
Groundwater: Quality	Quarterly		x		
Waste:					
Cellulose/lignin Ratio	Twice annually			x	
Ash Content	Twice annually			x	
Biological Methane Potential	Twice annually			x	
Appearance	Twice annually			x	

appearance of the waste. While examining exhumed waste from a DSWA landfill, Pohland (1992) concluded that low volatile solids content of the waste was a misleading parameter with respect to waste stability.

Conclusion

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 no longer threats to the environment. A specified design life of 20 yrs 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 significantly reduced. Similarly, gas production confined to a few years rather than decades provides opportunity for control and destruction of air toxics and greenhouse gases. With sufficient data acquired through monitoring of today's bioreactor landfills, regulators may come to reduce long-term 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 will translate into significant cost savings.