Active Municipal Waste Landfill Operation: A Biochemical Reactor

by

Debra R. Reinhart
Civil and Environmental Engineering Department
University of Central Florida
P.O. Box 162450
Orlando, Florida 32816-2450

CR 820318

Project Officer

David Carson
Remediation and Containment Branch
Land Remediation and Pollution Control Division
National Risk Management Research Laboratory
Cincinnati, Ohio 45268

National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

Abstract

The practice of landfilling of solid waste has evolved to produce a complex engineered facility. So-called advances in the design and operation of the modern landfill have resulted in a tendency to place waste material in a water-tight vessel, creating an environment which inhibits waste degradation. Under proper conditions, the rate of municipal solid waste biodegradation in a landfill can be stimulated and enhanced. Environmental conditions which most significantly impact biodegradation include pH, temperature, nutrients, absence of toxins, moisture content, particle size, and oxidation-reduction potential. One of the most critical parameters to MSW biodegradation has been found to be moisture content. Moisture content can be most practically controlled via leachate recirculation. Leachate recirculation provides a means of optimizing environmental conditions within the landfill providing enhanced stabilization of landfill contents as well as treatment of moisture moving through the fill.

Laboratory and pilot-scale studies have shown that moisture control permits rapid stabilization of waste, enhanced gas production, and improved leachate quality; reducing long-term environmental consequences and liability of waste storage and improving the economics of landfilling. Several dozen landfills have initiated efforts to recirculate leachate and full-scale documentation of the efficiency of this practice is now becoming possible.

This document describes experiences with bioreactor landfill operations from laboratory to full-scale. Studies which document the impact of bioreactor operation have been provided and operating and design criteria based on state-of-the-art facilities are described.

This report was submitted in fulfillment of contract number CR 820318 by the University of Central Florida under the sponsorship of the U.S. Environmental Protection Agency. this report covers a period from August 1992 through May 1995 and work was completed as of August 1995.

Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce envcironmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and ;made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

Contents

Figures

Tables

Number | Page

List of Abbreviations

AA	-- acetic acid
BOP	-- biological methane potential
BOD	-- biochemical oxygen demand
C	-- Celsius
COD	-- chemical oxygen demand
CSWMA	-- Coastal Solid Waste Management Authority
CSWMC	-- Central Solid Waste Management Center
d	-- day
DSWA	-- Delaware Solid Waste Authority
ft	-- feet
ha	-- hectare
kg	-- kilograms
l	-- liters
lbs	-- pounds
LFG	-- landfill gas
lpm	-- liters per minute
m	-- meters
MSW	-- municipal solid waste
NA	-- data not available
NYSERDA	-- New York State Energy Research and Development Authority
SC	-- specific conductivity
SUTRA	-- Saturated and Unsaturated Transport
TDS	-- total dissolved solids
TOC	-- total organic carbon
tpd	-- tons per day
TPD	-- metric tons per day
TS	-- total solids
TSS	-- total suspended solids
TVA	-- total volatile organics
TVS	-- total volatile solids
USGS	-- United States Geological Service
USEPA	-- United States Environmental Protection AGency

Acknowledgment

The research for this project was performed under the direction of Dr. Debra R. Reinhart with assistance from Dr. A. Basel Al-Yousfi. The contributions of the following graduate and undergraduate assistants are also recognized: Philip McCreanor, Santosh Agora, Ken Lewis, Mark James, and Michelle Marnitz.

Chapter 1
Introduction

While the typical citizen may think otherwise, the modern municipal solid waste (MSW) landfill has evolved into a sophisticated facility. The state-of-the-art landfill can be loosely categorized into four classes. The secure landfill tends to entomb wastes, perhaps postponing any environmental impact to the future when environmental controls and safeguards initially provided fail. The monofill accepts waste which cannot be processed otherwise through resource recovery, composting, or incineration. These materials tend to be inert and may be more easily assimilated by the environment. At present, the monofill is used for disposal of combustion ash, construction and demolition debris, and yard waste. The reusable landfill permits excavation of the landfill contents to recover metals, glass, plastics, other combustibles, compost and, potentially, the site itself following a lengthy stabilization period. A fourth, emerging landfill type, is the bioreactor landfill, which is operated in a manner to minimize environmental impact while optimizing waste degradation processes.

The landfill, as we know it, has evolved from a long tradition of land disposal of MSW, dating back to prehistoric times. Problems with land disposal began as society developed and population density increased. Land disposal of waste (often as open dumps) was subject to aesthetic, safety, and health problems which prompted innovations in design and operation. Environmental impacts associated with MSW landfills have complicated siting, construction, and operation of the modern landfill. Production of leachate has lead to documented cases of groundwater and surface water pollution. Landfill gas emissions can lead to malodorous circumstances, adverse health effects, explosive conditions, and global warming. Traffic, dust, animal and insect vectors of disease, and noise are often objectionable to nearby neighbors.

Ideally, land should be a repository exclusively for inert "earthlike" materials that can be assimilated without adverse environmental impact, a conviction held by landfill regulators, designers, and operators throughout the world (Carra and Cossu, 1990). However, successful application of this concept requires extensive waste processing to develop an acceptable product for land disposal, and faces challenges related to public opposition, economics, waste handling, and transportation of recovered materials. The most reasonable scenario for success appears to be a MSW management park, where regional facilities for managing waste, from separation to resource recovery/reuse to incineration to landfilling, would be collectively sited.

While disposal solely of inert materials may be an admirable objective, it will be some time, if ever, before this concept can be universally applied. It is likely, therefore, that landfills will continue to receive a variety of materials with potential for environmental impact. A second global consensus is that where leachable materials are land disposed, impenetrable barriers must be provided and waste stabilization must be enhanced and accelerated so as to occur within the life of these barriers, that is, the landfill must be designed and operated as a bioreactor. Additional advantages of the bioreactor landfill include increased gas production rates over a shorter duration, improved leachate quality, and more rapid landfill settlement. Clearly, to successfully operate the bioreactor landfill, it will be necessary to implement a variety of control mechanisms.

Under proper conditions, the rate of MSW biodegradation can be stimulated and enhanced. Environmental conditions which most significantly impact biodegradation include pH, temperature, nutrients, absence of toxins, moisture content, particle size, and oxidation-reduction potential. One of the most critical parameters affecting MSW biodegradation has been found to be moisture content. Moisture content can be most practically controlled via leachate recirculation. Leachate recirculation involves the return of liquid emanating from active or closed landfills back to the landfill and provides a means of optimizing environmental conditions within the landfill to provide enhanced stabilization of landfill contents as well as treatment of moisture moving through the fill. 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 at low additional construction and operating cost. It has been suggested that leachate recirculation can reduce the time required for landfill stabilization from several decades to two to three years (Pohland, 1975). Figure 1-1 provides a schematic of the landfill bioreator.

This report documents results of research efforts to demonstrate full-scale operation of a municipal solid waste landfill bioreactor such that it poses minimal risk to human health and the environment. Chapter 2 provides an executive summary of this report. Chapter 3 summarizes the regulatory status of the bioreactor landfill. A review of laboratory, pilot, and full-scale investigations of the bioreactor landfill in the technical literature is given in Chapter 4. Chapter 5 describes design and operating criteria for second-generation full-scale bioreactors constructed over the last five years. Chapter 6 provides an overview of the impact of bioreactor operation on landfill leachate and gas characteristics. Chapters 7 and 8 summarize state-of-the-art design and operating criteria for the bioreactor landfill, respectively.

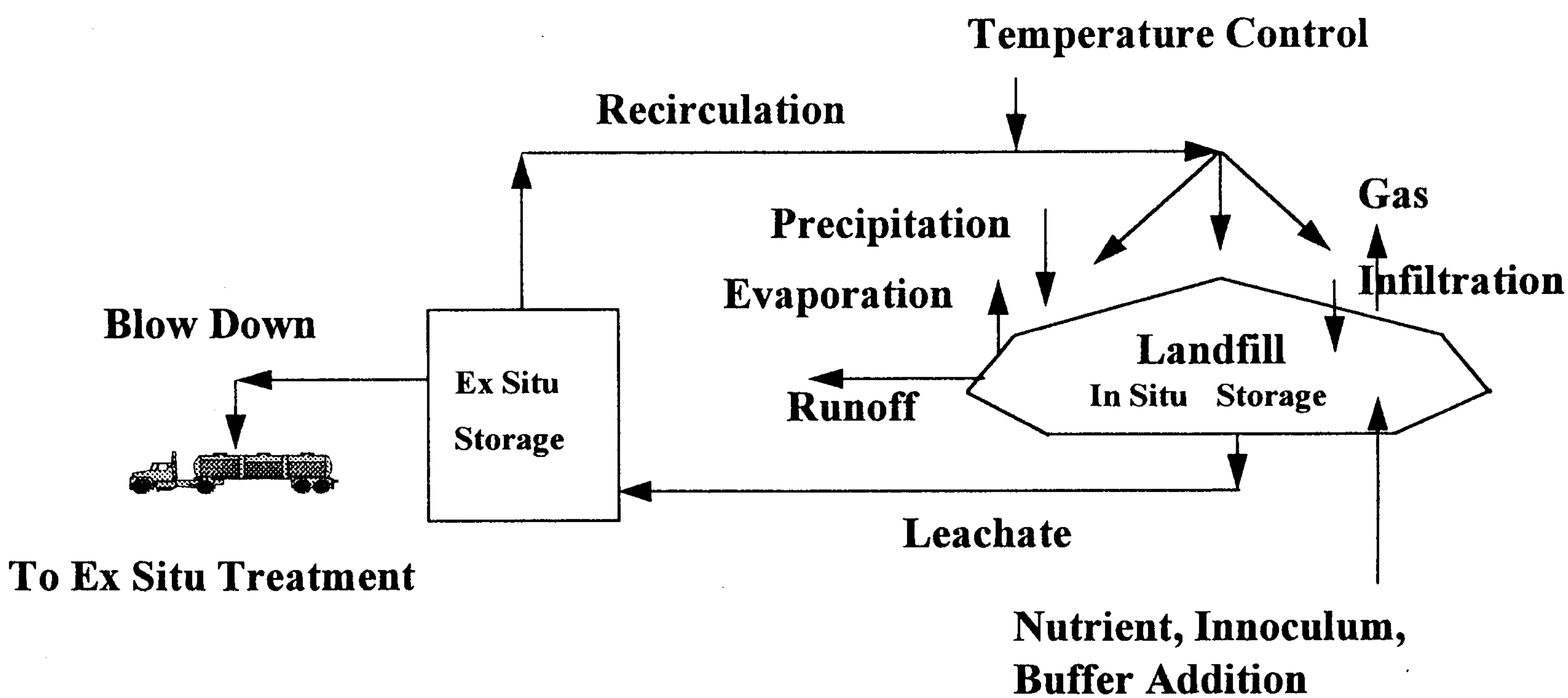


Figure 1-1. Schematic diagram of the landfill bioreactor.

Chapter 2
Executive Summary

Introduction

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

Under proper conditions, the rate of MSW biodegradation in a landfill can be stimulated, enhanced, and controlled within certain limits. Environmental conditions which most significantly impact biodegradation include pH, temperature, nutrients, absence of toxins, moisture content, particle size, and oxidation-reduction potential. Of these, the most critical parameter affecting MSW biodegradation has been found to be moisture content, which can be most practically controlled via leachate recirculation. Leachate recirculation provides a means of optimizing environmental conditions within the landfill, providing enhanced stabilization of landfill contents as well as treatment of moisture moving through the fill. This report documents results of research efforts to demonstrate full-scale operation of a municipal solid waste (MSW) landfill bioreactor (employing leachate recirculation and other enhancement processes) such that it poses minimal risk to human health and the environment.

Full-Scale Bioreactor Landfills

Multiple laboratory and pilot-scale investigation have been conducted to investigate the effects of enhancement techniques on leachate quality, waste stabilization rates, waste settlement, gas production, attenuation of heavy metals, and other factors. These studies have demonstrated that bioreactor operation can reduce the time required for landfill stabilization from several decades to two to three years. Full-scale studies of the 1980's investigated the use of bioreactor techniques (primarily leachate recirculation) to accelerate waste stabilization and largely confirmed results of laboratory and pilot-scale studies. However, regulators continued to express a lack of confidence in the method, specifically citing concerns over leachate collection system interference, geological and climate factors, freezing problems, leachate seepage, lack of waste absorptive capacity, and accelerated gas and odor production.

New generation bioreactor landfills are successfully recirculating leachate using leachate spraying, prewetting of waste, surface ponds, vertical injection wells, and horizontal subsurface introduction. From operating and design experience, the following conclusions can be made concerning full-scale bioreactor landfills.

- Storage is a critical design parameter. Sites with storage volume exceeding 700 m^3/ha report lowest leachate off-site management requirements.

- Where insufficient storage volume was provided, the volume of recirculated leachate represented over 50 percent of leachate generated. Also, large volumes of recirculated leachate tend to impact leachate quality more severely.

- Flexibility in leachate management operation is essential. A combination of devices (vertical and horizontal, for example) provides greatest wetting capacity.

- It is recommended that corrosion resistant materials be used and that leachate recirculation facilities be designed to accommodate landfill settling.

- Wetter areas tend to stimulate gas production.

- Use of low permeability intermediate and daily cover leads to leachate ponding and side seeps.

- Sufficient waste must be in place to absorb moisture to successfully recirculate leachate. Most sites recommend at least 6 m (20 ft) of waste in place prior to initiating leachate recirculation.

- Use of impermeable alternate daily cover such as a tarpaulin minimizes leachate production and facilitates leachate recirculation.

The Impact of Leachate Recirculation on Leachate and Gas Characteristics

Laboratory and pilot-scale studies have shown that moisture control permits rapid stabilization of waste, enhanced gas production, and improved leachate quality; reducing long-term environmental consequences and liability of waste storage and improving the economics of landfilling. Several dozen landfills have initiated efforts to recirculate leachate and full-scale documentation of the efficiency of this practice is now becoming possible. Leachate quality data were collected from five full-scale recirculating landfills and analyzed to contrast with data observed at conventionally operated landfills. From these data it appears that leachate characteristics of recirculating landfills follow a pattern similar to that of conventional landfills, *i.e.*, moving through phases of acidogenesis, methanogensis, and maturation (although few recirculating landfills have reached maturation). These data do not suggest that contaminants extensively concentrate in the leachate. As a matter of fact, the overall magnitude of various leachate components, during the consecutive phases of landfill stabilization, are quite comparable in both types of landfills.

Even in the case where recycled leachates are somewhat stronger than single-pass leachates, they are primarily treated within the landfill, utilizing its storage and degradation capacity as an effective bioreactor. No extra liability and/or handling requirements will result from such cases, because leachate is repeatedly recirculated back into the landfill until its strength diminishes and stabilizes. In this respect, frequency of recirculation can be employed as a control measure to optimize landfill operations and alter leachate characteristics as desired.

Studies have shown that leachate recirculation promotes reduced oxidation-reduction potential and stimulates methanogenesis, which in turn, enhances attenuation of a variety of organic pollutants. Furthermore, heavy metal concentrations at full-scale leachate recirculating landfills tend to be below detection limits, with the exception of iron, magnesium, and in one situation, arsenic. In the presence of leachate recirculation, iron concentrations tended to decline with time, while remaining constant in conventionally operated landfills. Where leachate recirculating sites were continuing to receive waste, however, iron concentrations remain elevated. The primary removal mechanism for metals in conventionally operated landfills appears to be washout, although limited chemical precipitation may occur. In leachate recirculating landfills, the primary removal mechanisms appear to be metal sulfide and hydroxide precipitation, and capture within the waste matrix by precipitation and encapsulation, sorption, ion-exchange, and filtration.

Once methanogenesis is established in both conventionally operated and leachate recirculating landfills, the leachate organic strength generally declines. In order to quantify the impact of leachate recirculation of leachate stabilization, a comparison of the rate of decline in the COD for recirculating and single-pass operations was made. Because of the limited available operational information for these studies, a rigorous kinetic analysis of the sequential reactions was not possible. However, a non-linear regression of chronological, declining COD data was performed for a series of laboratory studies of leachate recirculation and conventional, single-pass operations. From the rate of decline, COD half-lives can be calculated and compared. COD half-lives for recirculating operations ranged from 0.07 to 0.43 years, for single-pass landfills, 0.41 to 3.75 years.

A similar analysis of leachate COD for full-scale leachate recirculating landfills having moved to maturation phases was made. Here, half-lives ranged from 0.32 to 1.05 years, nearly five time greater than those of laboratory recirculating lysimeters. A full-scale landfill does not usually depict a single degradation phase, but rather overlapping phases representing various sections, ages, and activities within the landfill. In addition, unlike laboratory-scale columns, portions of the full-scale landfill may be relatively dry and experiencing slower decay rates.

Unfortunately, the efficacy of leachate recirculation in enhancing waste degradation relative to conventionally operated landfills at full-scale is difficult to quantify, because of the lack of conventional/recirculation parallel operations. Recognizing this limitation, leachate COD data were gathered from the literature for conventional landfills. The data were analyzed to determine a COD half-life as described above. A COD half-life of approximately 10 years was calculated for conventional landfills as compared with values of 230 to 380 days for recirculating landfills. Clearly, recirculation significantly increases the rate of the disappearance of organic matter in leachate and by inference, the rate of waste stabilization. Results for conventional landfills calculated in this study compare favorably with half-life values for waste degradation reported in the literature, which ranged from ten to 100 years.

Gas production is relatively easy to determine from laboratory lysimeters, however full-scale measurement of gas emissions from active sites is more difficult to achieve. Limited data suggest that, as in lysimeters, gas production is significantly enhanced at full-scale landfills as a result of both accelerated gas production rates 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).

Landfill Bioreactor Design

In many ways, the design of the modern MSW landfill is dictated by state and federal regulation. The design components most critical to the landfill include the liner and leachate collection system, leachate management facilities, gas collection and management facilities, and the final cap. These same components must be adapted to the landfill bioreactor to manage greater volumes of leachate, to incorporate leachate introduction, and to handle enhanced gas production. Since this technology is in its infancy this discussion will reflect state-of-the-art practice; improvements in bioreactor landfill design are expected and desired.

The conventional liner/leachate collection system utilizes a composite, double, or double composite liner with geosynthetic and natural soil components. Subtitle D of RCRA requires that a composite liner be present when leachate recirculation is employed. 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, alternatively, 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. Filter clogging is expected and difficult to control, therefore a safety factor should be used in selecting the design filter permeability and the geotextile should be placed over much of the landfill footprint rather than wrapping the collection pipe. 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. Field experience with leachate recirculation have encountered excess heads on the liner, however only when ex situ storage and treatment is limiting.

At sites where large storage volumes were provided relative to the size of the landfill cell, off-site management was minimized. 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. 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. 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. 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 sufficient ex situ storage and/or off-site management is not sufficient to permit timely removal of leachate.

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. Prewetting of waste has advantages in terms of simplicity, evaporation opportunity, and a uniform and efficient use of waste moisture holding capacity, however it is labor intensive and incompatible with final closure. Leachate spraying is flexible and provides for great opportunity for volume reduction, however, odor and misting are potential problems and spraying cannot be used during periods of rain or freezing and following closure. Surface ponds also offer advantages of simplicity, but have a limited impact area and tend to collect stormwater. Vertical injection wells are frequently used and are easily and cheaply installed during landfilling, however wells tend to interfere with daily operations and have limited impact areas as well. Horizontal subsurface introduction seems to be the current method of choice due to its wide impact area and ease of installation. Landfill subsidence may adversely affect horizontal systems and long-term use may result in biofouling.

A combination of methods is the most desirable approach to leachate recirculation. Initial wetting with leachate as the waste is placed is also recommended. Once sufficient waste is in place, horizontal trenches and vertical wells can be utilized. Trench spacing guidance is provided based on hydrodynamic modeling. Vertical well spacing is conventionally 35 to 100 m (118 to 333 ft).

Gas production enhancement through bioreactor operation 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, perhaps using horizontal extraction trenches or phased closure. 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.

For economic reasons, the recent trend in landfill construction is to build deep cells which provide a life of two to five 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 be proven inefficient. Small, hydraulically separated cells are easier to isolate to minimize stormwater contamination and shed water more efficiently when covered. Once closed, optimal methanogenic conditions within the cell develop and gas production and collection is facilitated. It may also be possible to then 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. In addition, postponement of final RCRA closure should be considered to allow for placement of an interim cap which provides for limited infiltration of moisture, along with leachate recirculation, to maintain appropriate conditions for biodegradation.

Landfill Bioreactor Operation

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

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. Higher compactions have 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. Low initial density apparently stimulates waste degradation which may lead to higher long-term density and volume recovery.

Particle size can be reduced through shredding prior to waste placement. Shredding promotes a more uniform waste and reduces fire potential, blowing wastes, and the need for daily cover. In addition, more waste is exposed to microbial activity and consequently biodegradation may be enhanced. Shredding also improves water distribution and provides more even settlement. 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 gas production and long-term liability reduction to justify the cost.

Reduction-oxidation (redox) conditions within the landfill establish waste degradation pathways. High redox potential associated with aerobic conditions provides for accelerated waste stabilization and reportedly improved leachate quality, but may lead to internal fires if not controlled properly. 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).

Moisture addition has been demonstrated repeatedly to have a stimulating effect on methanogenesis although some researchers indicate that it is the movement of moisture through the waste as much as it is water addition that is important. Recommended moisture content reported in the literature ranges from a minimum of 25 percent (wet basis) to optimum levels of 40 to 70 percent. Increased moisture content also permits significant storage of moisture within the fill.

Frequency of leachate recirculation, on a practical basis, is generally dictated by the inventory of accumulated leachate. Operators will be more or less looking for a place to put large volumes of water. Such practice can lead to saturation, ponding, and 'acid-stuck' conditions. A more preferable procedure employed at several successful operations is to slowly introduce leachate at first by rotating from one area to another, allowing areas to rest between recirculation episodes. This procedure facilitates gas movement and minimizes saturation which is particularly important during early phases of the degradation process. Once gas production is well established, leachate can be recirculated to that area more frequently. Leachate recirculation should be initiated as soon as possible following waste placement (once sufficient waste is present to absorb the recirculated liquid) to ensure proper moisture content for biodegradation. 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 wetting 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.

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 closed landfill 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 within the closed cell and moisture control for the active cell. 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.

The consortium of microorganisms involved in the stabilization of waste has specific environmental requirements including, among others, pH, temperature, and micro- and macro-nutrients. Because waste degradation involves biochemical reactions, the rate of degradation tends to increase with temperature up to a maximum value. Nutrient requirements are generally met by the waste at least during early degradation phases although phosphorous may be limiting during later stages. Optimum pH for methanogens is approximately 6.8 to 7.4 and buffering of leachate in order to maintain pH in that range has been found to improve gas production in laboratory and pilot studies. 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. 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, in some cases stimulating early onset of methane production, but rarely increasing long-term gas production.

As moisture moves through the landfill, 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. 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 are removed prior to the 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.

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 such operation offers opportunity to control the process. Monitoring of gas recovery and composition, waste characteristics, leachate flow and composition, liner integrity, and waste settlement have been recommended.

Once waste stabilization has been satisfactorily achieved, the cell should be deactivated by discontinuing leachate recirculation and removing all excess 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. Sufficient waste stabilization appears to occur when gas production reaches relatively low rates and leachate strength remains low. Other indicators are low leachate BOD\COD ratio (less than 0.1), cellulose/lignin ratio less than 0.2, low biological methane potential (less than 0.045 m^3/kg volatile solids added), and the appearance of the waste (dark and sludge-like).

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 is no longer a threat to the environment. A specified design life of 20 years for geosynthetic membranes may not provide adequate protection for the conventional landfill with stabilization periods of many decades. The potential impact on groundwater from a cleaner leachate is 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, 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 minimal monitoring would translate into significant cost savings.

Chapter 3
Regulatory Status

Regulations promulgated under RCRA Subtitle D allow leachate recirculation, provided a composite liner and leachate collection system are included in the design. In the preamble to Subtitle D regulations, implemented in 1991 (US EPA, 1988), EPA commented that :

> ". . . EPA recognizes that landfills are, in effect, biological systems that require moisture for decomposition to occur and that this moisture promotes decomposition of the wastes and stabilization of the landfill. Therefore, adding liquids may promote stabilization of the unit. . ."

Specifically, Section 258.28(b)(2) of CFR Part 258, "Criteria for Municipal Solid Waste Landfills" states the following:

> "Bulk or noncontainerized liquid waste may not be placed in a municipal solid waste landfill unit unless ... the waste is leachate or gas condensate derived from the municipal solid waste landfill unit and the landfill unit is equipped with a composite liner and a leachate collection system that is designed and constructed to maintain less than a 30-cm depth of leachate over the liner."

A telephone poll of US state regulatory agencies was conducted in late 1992 and early 1993. The results of this poll are provided in Table 3-1. To summarize, full-scale operation of leachate recirculation was practiced at that point in time (or would be soon) in twelve states and was permissible in all but seven states. Recirculation facilities were in place at landfills in eight states, under construction at landfills in four states, and planned at landfills in several other states.

For the most part, states merely adopted RCRA criteria, requiring a composite liner. A few states identified additional, more stringent criteria for leachate recirculation. For example, Florida, Georgia, Pennsylvania, and Virginia specifically address odor prevention. Florida requires gas management facilities in place prior to commencement of leachate recirculation. New York requires a double composite liner for all MSW landfills. Pennsylvania and Georgia require that the leachate recirculation piping system be installed under a permeable intermediate cover. Virginia, New York, Georgia, and Florida require control of runoff and prohibit ponding. Georgia also requires that sufficient waste be in place to provide sufficient moisture absorption prior to initiating recirculation.

Those states which prohibited leachate recirculation did so for several reasons. Regulators cited a lack of confidence in the method, interference with the leachate collection system, geological and climate concerns, freezing problems, leachate seepage, lack of waste absorptive capacity, and accelerated gas and odor production. A summary of comments from state regulators is provided as Appendix A.

Table 3-1. 1993 Status of Recirculation in the United States*

State	Regulations do not Permit Recirculation	Recirculation Permitted	Recirculation in Place
Alabama		X	
Alaska		X	
Arizona		X	
Arkansas		X	X
California		X	X
Connecticut		X	
Colorado		X	
Delaware		X	X
Florida		X	X
Georgia		X	X
Idaho		X	X
Indiana		X	
Illinois		X	X
Iowa		X	
Kansas		X	
Kentucky		X	
Louisiana	X		
Maine		X	
Maryland		X	X
Massachusetts		X	
Michigan		X	
Minnesota	X		

Table 3-1. Continued

State	Regulations do not Permit Recirculation	Recirculation Permitted	Recirculation in Place
Mississippi		X	
Missouri		X	X
Montana		X	
Nebraska		X	
Nevada		X	
New Hampshire		X	X
New Jersey	X		
New Mexico		X	
New York		X	X
North Carolina		X	X
North Dakota		X	
Ohio	X		
Oklahoma		X	
Oregon	X		
Pennsylvania		X	X
Rhode Island		X	
South Carolina	X		
South Dakota		X	
Tennessee		X	
Texas		X	
Utah		X	
Vermont		X	

Table 3-1. Continued

State	Regulations do not Permit Recirculation	Recirculation Permitted	Recirculation in Place
Virginia		X	
Washington		X	
West Virginia	X		
Wisconsin	X		
Wyoming		X	

* A summary of regulator comments in provided as Appendix A

Chapter 4
Literature Review - Landfill Bioreactor Studies

Laboratory-Scale Studies

Many laboratory-scale studies have been conducted to investigate the effects of leachate recirculation on leachate quality, waste stabilization, waste settlement, gas production, attenuation of heavy metals, and other factors. The studies were primarily carried out in the United States, United Kingdom, and the former Federal Republic of Germany.

Moisture content, pH, temperature, availability of macro- and micro-nutrients and the presence of suitable microorganisms are the main parameters controlling the process of landfill stabilization and are therefore the parameters typically manipulated in the laboratory studies. Moisture content can be controlled by the addition of regulated quantities of water and/or leachate. The pH can be controlled by adding buffering compounds. Macro- and micro-nutrients are usually present in sufficient quantities in the waste and do not act as limiting factors in the stabilization process, hence nutrients are usually not added. Presence of suitable microorganisms responsible for stabilization can be ensured by adding anaerobically digested sludge in which acclimated anaerobic and facultative microorganisms are present. Several laboratory-scale studies are described below. The studies included are by no means all of the pertinent studies reported in the literature. Other studies include those of Mata-Alvarez and Martina-Verdure (1986), Barlaz, et al (1990), Buivid, et al (1981), Chian (1977), and Klink and Ham (1982).

Georgia Institute of Technology Experiment I (Pohland, 1975)

One of the first experiments on leachate recirculation was conducted at the Georgia Institute of Technology in the mid-1970's and supported by the USEPA. This experiment, which conclusively proved the effectiveness of leachate recirculation on waste stabilization, is described below.

Four test columns, each 0.9 m (3 ft) in diameter, were filled with 3 m (10 ft) of MSW and compacted to a density of 357 kg/m^3 (535 lb/yd^3). A 0.76-m (2.5-ft) soil cover was placed over the compacted coarsely-ground waste mass. The first column was a control cell with no leachate recirculation (single-pass cell). The second column was subjected to leachate recirculation only. In the third column, leachate recirculation was coupled with pH control (using NaOH) to maintain near neutral conditions. Leachate recirculation with pH control in addition to initial seeding (with wastewater sludge) was used for the fourth column. Leachate recirculation was accomplished by pumping through a distribution system located on top of the waste but below the cover soil. Approximately

945 l (250 gal) of water were added to all of the cells to produce leachate immediately. Leachate was drained to separate sumps from which samples were collected and analyzed at regular intervals for 1100 days after the start of the experiment.

For the control column, Chemical Oxygen Demand (COD) increased rapidly and peaked at about 19,000 mg/l after about 200 days and declined gradually to about 4,000 mg/l after 1,000 days. Total volatile acids (TVA) concentration showed a similar pattern, peaking at about 10,000 mg/l after 200 days and declining to 2,000 mg/l after 1,000 days. The pH did not show much variation and was in the acidic range of 5.0 to 6.5 throughout 1100 days of monitoring.

For the second column, with leachate recirculation only, the variation of COD, TVA, and pH with time was significantly different from the control cell. COD increased more rapidly than the control column, peaking at 11,000 mg/l after 100 days. After 150 days, COD decreased to a low of 4,000 mg/l and then decreased gradually to about 250 mg/l by day 500. TVA concentration variation followed the pattern of COD variation, peaking to 6,000 mg/l at 200 days, but increased again at 250 days, reaching 1,500 mg/l at 400 days and declined gradually to less than 200 mg/l by day 700. The pH remained around 5.0 for the first 200 days. As the COD and TVA concentrations dropped, pH increased to about 7.0 after 500 days and remained in the neutral region thereafter.

Column 3 with leachate recirculation and pH control, showed a more rapid decrease in TVA and COD concentrations than the second column. Both COD and TVA peaked after 150 days at 10,000 mg/l and 5,000 mg/l, respectively. After 200 days, COD concentration had decreased to less than 500 mg/l and TVA concentration to less than 250 mg/l. Due to the addition of buffers, pH was near neutral throughout the monitoring period.

The fourth column, with leachate recirculation, pH control and seeding, did not perform better than the pH-controlled leachate recirculating column (Column 3). Peak COD and TVA concentrations were 9,000 mg/l and 5,000 mg/l respectively, both occurring at about 60 days. While the TVA concentration declined to near zero at 400 days, COD concentration reached near zero at 650 days. Initially, pH dropped to nearly 5, but due to buffering, was in the neutral region after day 150 and throughout the remaining monitoring period.

The following important observations can be made from the results of this laboratory simulation.

- Leachate recirculating columns produced low COD/TVA leachates in a shorter time period as opposed to a more gradual decline in the control cell.

- The peak COD and TVA concentrations in the leachate recirculated columns were less than the control column.

- pH remained more neutral in the leachate recirculated column than the control column.

- pH control and leachate recirculation gave the best performance with rapid decline in COD and TVA concentrations.

- Inoculation with wastewater sludge did not accelerate the degradation process.

The most significant inference which can be drawn from this experiment is that leachate recirculation accelerates the waste degradation process as characterized by a rapid decrease in the COD and TVA concentrations. Although this was one of the first experiments in the area, it convincingly proved the effectiveness of leachate recirculation.

University of Louisville Experiment (Tittlebaum, 1982)
A laboratory-scale study, supported in part by the Illinois Institute on Environmental Quality, was conducted to demonstrate the advantages of leachate recirculation and to investigate the feasibility of leachate recirculation systems in providing leachate treatment. An additional objective was to determine of the effect of leachate pH and nutrient control on biological stabilization of shredded and unshredded refuse.

Four 0.9-m (3-ft) diameter steel test cells, equipped with leachate collection and redistribution (except the control cell) systems, were set up and filled to 2.4 m (8 ft) with domestic refuse compacted to a density of 240 kg/m^3 (400 lbs/yd^3). Test Cell 1 was the control cell with unshredded refuse. Cell 2, with leachate recirculation, contained shredded refuse with 70 percent moisture content and pH control (using NaOH). Cell 3 was operated similarly to Cell 2 except that it contained unshredded refuse. Test Cell 4 had nutrient control (phosphorus and nitrogen addition) and was similar to Cell 3 in all other aspects. Approximately 11 m^3 (200 gal) of water were added to start leachate production in Cells 2, 3, and 4. Tap water, equivalent to the total daily rainfall, was routinely added to all of the cells. Leachate from all the cells was periodically analyzed for 514 days. The data obtained showed that leachate recirculation resulted in marked decrease in the concentrations of TVA, Biochemical Oxygen Demand (BOD), COD, and Total Organic Carbon (TOC) in Cells 2, 3, and 4 in comparison to Cell 1. Cell 1 appeared to be acid stuck, maintaining high levels of TVA throughout the test period, although pH remained at neutral levels. Because all three leachate recirculating cells produced consistent leachate quality, nutrient control was found not to have any significant impact on leachate quality nor did shredding of waste increase the rate of stabilization. The BOD/COD ratios were observed to be close to those reported for municipal wastewater (between 0.6 to 0.8) in all four cells, indicating the biological treatability of leachate in wastewater treatment plants should off-site treatment of leachate be required. Based on the analytical data obtained for all the cells, the following conclusions were drawn.

- Leachate recirculation with pH control established anaerobic biological population in the fill rapidly.

- Nutrient control did not have any significant effect on stabilization of organic content of the refuse.

- Shredding did not have any effect on biological stabilization of the refuse.

- Leachate recirculation with pH control lead to accelerated biological stabilization of the organic content of the refuse thereby reducing the time required for ultimate site use (land reclamation).

- Leachate recirculation with pH control lead to significant reductions in BOD, COD, and TOC.

- Leachate recirculation with pH control can be used as an effective leachate treatment process.

German Experiment (Doedens and Cord-Landwher, 1989)
Test cell experiments on leachate recirculation were conducted in the former Federal Republic of Germany. Four steel cylindrical test cells, each 1.5 m (4.9 ft) in diameter were installed and filled with 1.35 m (4.4 ft) of shredded waste compacted to a density of to 20,800 to 23,200 kg/m^3 (1300 to 1450 lb /yd^3) wet weight to simulate the actual density achieved in field by compactors. The waste volume in each cell was 2.4 m^3 (85 ft^3) and the initial moisture content was 24 to 31 percent. All of the cells were air tight, temperature controlled (35°C), and equipped with leachate redistribution system and meters to measure leachate and gas flows.

Test Cell 1 received rainwater equivalent to 660 mm/yr (26 in/yr) of precipitation and all the leachate generated was redistributed to the cell. The remaining Cells (2, 3, and 4) received rainwater equivalent to 330 mm/yr (13 in/yr) precipitation (half that of Cell 1). Test Cell 2 was the control cell receiving rainwater only with no leachate recirculation (single-pass cell). Test Cell 3 received rainwater (330 mm/yr) (13 in/yr) and all the leachate generated was fed back to the cell along with rainwater. The fourth cell was initially brought to field capacity with leachate from a stabilized landfill. Thereafter, the cell received 330 mm/yr (13 in/yr) rainwater in addition to all of the leachate generated.

Test Cell 1 showed a more rapid decline in the COD concentration than any other cell. Test Cell 2, the control cell, took longer than any other cell to reduce COD concentration to levels comparable to other cells. After about 300 days from the start of the experiment, Test Cell 1 had the lowest COD concentration and Test Cell 2 had the highest concentration. Test Cells 3 and 4 produced approximately the same COD concentrations, which were higher than Test Cell 1 and lower than Test Cell 2. However, since varying quantities of water were added to each of the cells, the total mass loads emitted from the cells should be considered rather than concentrations. For example, although the COD concentration is less in Test Cell 1, the total load emitted would be more because the cell received twice the amount of water than that of other cells. Considering the loads withdrawn from the test cells during the test period (excluding the loads in recycled leachate), Test Cell 3 gave the best result with the lowest mass emission (during the test period) of COD, BOD, chloride, zinc, lead, and cadmium compared to remaining cells.

Cell 4 had the highest emission loads of COD, BOD, chloride, zinc, lead, and cadmium due to its initial saturation with stabilized landfill leachate. Cell 1 (with leachate recirculation) performed better than Cell 2 (control cell) with respect to emission loads of COD, BOD, chloride, zinc, lead and cadmium. Control Cell 2 (single-pass cell) produced more gas than any other cell (114 m^3/t dry matter (3650 ft^3/ton)), followed by Cell 3 at 111 m^3/t dry matter (3560 ft^3/ton) and Cell 4 at 105 m^3/t dry matter (3360 ft^3/ton). Cell 1 produced significantly less gas than any other cell (50 m^3/t dry matter (1600 ft^3/ton)). Excluding Cell 4, which was initially saturated with leachate, the two leachate recirculating cells performed better (with respect to leachate quality) than the control (single-pass) cell. The most significant inference from this experiment is that leachate recirculation lowers the emitted loads of COD, BOD, chloride, and metals.

Newcastle University Experiment (Otieno, 1989)

Lysimeter studies were conducted at Newcastle University, U.K. to investigate the effect of leachate recirculation on different types of wastes and under various operating conditions. Four lysimeters, each 0.5 m in diameter, were filled with various types of domestic wastes and compacted to different densities. Depth of the columns was not indicated. The lysimeters were equipped with leachate distribution piping, leachate monitoring systems, and gas monitoring systems. Lysimeter 1 was filled with fresh crude domestic waste with a moisture content of 61 percent, and a density of 383 kg/m^3 (648 lbs/yd^3) while Lysimeter 2 was filled with the same type of waste and moisture content but was compacted to a density of 418 kg/m^3 (702 lbs/yd^3). Lysimeter 3 consisted of shredded domestic refuse with a moisture content of 44 percent and density of 306 kg/m^3 (513 lbs/yd^3). Lysimeter 4 consisted of aged domestic refuse with a moisture content of 85 percent and density of 550 kg/m^3 (34 lbs/ft^3). Lysimeter 2 was operated under saturation conditions while all others were operated with free draining leachate. The lysimeters were monitored over a period of 400 days.

Leachate from Lysimeter 3 with shredded refuse and the lowest density, showed a marked decrease in COD concentration within a shorter time than Lysimeters 1 and 2. Lysimeter 4, with aged refuse, had a very low COD leachate throughout the test period. Lysimeters 1 and 2 leachates had approximately the same COD concentration which was significantly higher than Lysimeter 3. Similar results were observed with respect to TOC concentrations. Results were similar with respect to TVA and BOD concentration variations, with Lysimeter 3 showing a dramatic decrease within a shorter time when compared to Lysimeters 1 and 2 and Lysimeter 4 having low concentrations throughout. Clearly, Lysimeter 3 performed better than any of the other lysimeters with the exception of Lysimeter 4 containing aged refuse. The following conclusions can be drawn from the results of this experiment.

- Shredding of refuse increases the degradation rate thereby producing better quality leachate in a shorter period of time.
- Lower density helps in increasing the degradation rate.
- Operation under saturation conditions does not result in any benefits with respect to

waste degradation, but rather may lead to higher strength leachates.

Georgia Institute of Technology Experiment II (Pohland, et al., 1992)
Another USEPA sponsored laboratory-scale experiment was conducted at the Georgia Institute of Technology to study the influence of leachate recirculation and single-pass operation on selected inorganic and organic priority pollutants codisposed with shredded municipal solid waste.

The experimental setup consisted of ten simulated landfill columns (steel cylinders) 0.9 m (3 ft) in diameter and 3 m (10 ft) in height. Each column was lined with 30-mil (0.076-cm) High Density Polyethylene (HDPE) liner and equipped with leachate collection and moisture/leachate distribution system. Each column was filled with 378 kg (832 lb) of shredded municipal solid waste. Organic and/or inorganic priority pollutants were added to the columns (except control columns) in varying doses. Metal sludges (constituting inorganic priority pollutants), prepared by mixing sawdust and metal oxides to obtain low, medium or high loadings were added to the columns. Two identically loaded columns, one with single-pass operation and another with leachate recirculation, constituted a pair of columns giving a total of five pairs of columns as shown in Table 4-1.

Table 4-1. Column Loading Characteristics (Pohland, et al, 1992)

Column	Operation	Initial loading height (cm)	Compact Density (kg/m^3)	Inorganic Pollutant Added*	Organic Pollutant Added#
1 CR	Recycle	29	313	None	None
2 C	Single Pass	30	301	None	None
3 O	Single Pass	29	309	None	Yes
4 OL	Single Pass	28	327	Low	Yes
5 OM	Single Pass	30	305	Medium	Yes
6 OR	Recycle	28	317	None	Yes
7 OLR	Recycle	29	309	Low	Yes
8 OH	Single Pass	30	305	High	Yes
9 OMR	Recycle	29	313	Medium	Yes
10 OHR	recycle	31	293	High	Yes

*Low: Cd=35 g, Cr=45 g, Hg=20 g, Ni=75 g, Pb=105 g, Zn=135 g, Medium: Low doubled, High: Medium doubled
#120 g each of 12 different organic compounds.

Leachate and gas samples were routinely analyzed for three years for admixed pollutants and other parameters. Overall, significantly greater volumes of gas at higher rates were produced in recycling columns vs. single-pass columns (averaging 42 m^3 (1500 ft^3) and 8.1 m^3 (290 ft^3) respectively) indicating an enhanced degree of waste stabilization. A prolonged acid phase was experienced in all columns requiring the addition of anaerobically digested sludge to initiate methane fermentation. During this time TVA concentrations reached 15,000 mg/l in recycle columns and 5 to 10,000 mg/l in single-pass columns. Leachate strength (as indicated by COD and TVA concentrations) decreased and gas production increased only after the onset of the methanogenesis phase after approximately 720 days. Thereafter, there was a dramatic decrease in COD and TVA concentrations along with an increase in pH and gas production in leachate recirculated columns with more moderate changes in single-pass columns. Gas production, also stable initially, dramatically increased with the onset of methane fermentation.

Priority pollutants caused a delay in the stabilization process in recycling columns and total inhibition in single-pass columns as demonstrated by lower pH values, gas production, and higher TVA concentrations relative to the control column. With respect to heavy metals, both recirculating and single-pass columns were capable of assimilating added pollutants, however recycle columns demonstrated greater capacity. Single-pass and leachate recycle columns exhibited little difference with respect to the release patterns of organic priority pollutants like dibromomethane, trichloroethane, and nitrobenzene. Leachate containment by recirculation, in addition to providing in-situ leachate treatment, resulted in efficient conversion to gas of many organic leachate constituents which otherwise would have been washed out.

Pilot-Scale Bioreactor Studies

A number of pilot-scale studies were conducted in the U.S. and other European countries to investigate the effects of leachate recirculation on landfill stabilization, leachate quality, landfill gas production and other parameters. Moisture content, waste density, type of waste, pH, temperature, nutrients, and seeding (addition of sludge) were typically controlled and manipulated in the pilot-scale studies. Several pilot-scale studies are briefly described below. A detailed compilation of test cell data has been provided elsewhere (IEA Expert Working Group on Landfill Gas, 1995).

Sonoma County, California (Emcon, 1976; Leckie, et al., 1979)

A pilot-scale landfill project was started in 1972 at Sonoma County, California, to study the effect of moisture on the rate of refuse stabilization, and on leachate quantity and quality. Five large-scale field test cells, each 15 m (49 ft) by 15 m (49 ft) by 3 m (10 ft), were constructed, filled with municipal solid waste compacted to 630 kg/m^3 (1000 lb/yd^3), and subjected to different operating conditions (moisture regimes). Each cell served a specific purpose and was operated accordingly as shown in Table 4-2. The cells were monitored for 900 days to evaluate leachate quality, gas composition, and settlement.

Cell A was the control cell, Cell B was initially brought to field capacity, Cell C received water at a rate of 3.8 m^3/d (1000 gal/d), Cell D was subjected to leachate recirculation, and Cell E was initially inoculated with septic tank pumpings. After construction, Cells A, B, and E received moisture only from infiltrating rainwater. The rate of leachate recirculation (in Cell D) varied from 1.9 to 19 m^3/day

Table 4-2. Test Cell Moisture Conditions, Sonoma County (Leckie, et al, 1979)

Cell	Purpose	Initial Liquid condition	Liquid Used in Initial Conditioning	Daily Liquid Application, m^3/d*	Liquid Used for Daily Liquid Application
A	Control Cell	None	None	None	None
B	High initial water content	Field Capacity	Water	None	None
C	Continual addition of water	None	None	0.76 - 3.8	Water
D	Leachate recirculation	None	None	1.9 - 3.8	Leachate
E	Microbial seeding	Field Capacity	Septic Tank Pumpings	None	None

* Other than infiltrating liquid

(500 to 5,000 gal/day). The leachate organic strength for Cells C and D with water input gradually declined. Leachate recirculation provided a more rapid decline in COD concentration than all other cells. The data from Cell D on gas composition also indicated an increased rate of biological stabilization. Based on the performance evaluation of Cell D and comparison with other cells, the following specific conclusions with respect to leachate recirculation were made.

- Leachate recirculation significantly increased the rate of establishment of anaerobic microbial population within the fill as suggested by gas quality.
- Leachate recirculation increased the rate of biological stabilization of the organic fraction of the refuse (as evidenced by reductions in BOD, COD, and TVA concentrations in leachate).
- Settlement was enhanced by liquid flow and accelerated microbial activity with leachate recirculation (20 percent reduction in height for leachate recirculating cell vs 7.6 percent for remaining cells).
- Continual flow-through of water increased rate of stabilization but created large volumes of leachate requiring ex-situ treatment.
- The addition of septic tank pumpings (inoculum) accelerated acid fermentation and was not beneficial in the absence of pH control and leachate recirculation.
- In the presence of leachate recirculation, the landfill acted as an anaerobic digester in treating leachate and therefore was found to be the most feasible and beneficial management strategy utilized in the study.

Georgia Institute of Technology Study (Pohland, 1980)
Pilot-scale investigations were conducted at the Georgia Institute of Technology to study the effects of leachate recirculation and to augment the results of initial laboratory-scale studies also conducted at Georgia Institute of Technology. Two simulated concrete landfill cells, each 3 m (10 ft) by 3 m (10 ft) by 4.3 m (14 ft) deep were constructed and filled with 3 m (10 ft) of shredded municipal solid waste compacted to a density of 319 kg/m^3 (537 lb/yd^3). One cell was left open to incident rain and the other was sealed completely to permit gas collection and eliminate evaporation. The cells were allowed to reach field capacity over a year's time. The sealed cell received tap water equivalent to rainfall received by the open cell through the distribution system. Both of the cells were equipped with leachate collection and distribution systems.

Nominal leachate production began on September 1, 1977, about a year after the completion of filling operations (August 13, 1976). Available leachate was recycled on a weekly basis. Daily recirculation of 760 l/day (200 gal) per cell was started on day 208. On day 346, the quantity of leachate recirculated was reduced to percolation capacity of the open cell. Recycling on alternate days was started on day 401 and was gradually reduced to 150 to 190 l/day per cell (40 to 50 gal/day).

Leachate samples were collected from both cells at regular intervals and analyzed for various parameters including BOD, COD, TOC, TVA, pH, phosphorus, chloride, and selected metals. Gas samples were also analyzed for carbon dioxide, nitrogen, methane, and hydrogen. TOC, COD and BOD, the critical parameters indicative of pollution potential of leachates, displayed similar pattern of decrease in concentrations for both cells. Data obtained during initial periods of weekly recirculation were somewhat erratic, more so for the sealed cell due to uneven distribution of TOC, COD and BOD after initiation of daily circulation. Although there was not much difference in concentrations of TOC, COD and BOD toward the end of the test period (520 days after leachate production began) concentrations were lower in the sealed cell than the open cell. TVA concentrations in both the cells initially increased and later decreased to levels below detection. The sealed cell provided a more congenial environment to methane formers by excluding oxygen. Gas production in the sealed cell increased to a high of 0.64 m^3/d (23 ft^3/d) with a CH_4 content of 57 percent, coinciding with the decrease in TVA concentration and increase in pH. Gas production decreased to 0.01 to 0.02 m^3/d (0.35 to 0.7 ft^3/d) by the end of the test period indicating that most of the readily available organics in the leachate were converted to gas within three months. Based on the differences in chloride concentrations between the two cells, moisture loss in the open cell due to evaporation was estimated between 20 to 30 percent of the incident rainfall.

This pilot-scale study supported the results of the previous laboratory-scale studies and demonstrated the advantages of leachate recirculation in rapid stabilization of readily available organic constituents accompanied with increased gas production rate in short time period.

Mountain View Landfill, California (Emcon, 1987; Pacey, et al,1987)

The objective of the pilot scale demonstration project conducted at Mountain View Landfill, California, was to study the effectiveness of the methods used to enhance methane gas generation. The key factors controlled and manipulated were moisture addition, buffer, inoculation, and leachate recirculation. However, as testified by refuse analysis, there was no effective control over moisture content due to excessive water infiltration into the test cells.

Six separate cells (designated A through F) were constructed for the study purpose. Each cell was approximately 31 m by 31 m (100 ft by 100 ft) and contained 14 m (47 ft) of waste. Cell F was the control cell and partial leachate recirculation was provided for Cell A. The other cells were not subjected to leachate recirculation. Composition of the cells at the beginning of the project (June, 1981) is shown in Table 4-3. The cell characteristics and monitoring results after 1597 days (through December, 1985) are presented in Table 4-4.

The results with respect to leachate recirculation were not in agreement with other studies. The total gas production rates were lower than the rates obtained in other lysimeter studies. Cell D, with no sludge addition, yielded the maximum amount of gas even though the moisture content (as compared

Table 4-3. Cell Composition After Construction, Mountain View (Pacey, et al, 1987)

Cell Component	Cell					
	A	B	C	D	E	F
Additions*	sbrw	sb	sbw	b(w)	s(w)	nône
Dry Refuse Solids (million kg)	4.88	5.42	4.81	6.00	4.96	5.64
Refuse Associated Water (million kg)	1.63	1.81	1.60	2.00	1.65	1.88
Porosity (%)	50	49	50	49	51	48
Dry Sludge Solids (million kg)	0.16	0.13	0.07	0	0.06	0
Sludge Associated Water (million kg)	0.88	0.73	0.38	0	0.31	0
Sludge in Place (million kg)	1.03	0.86	0.44	0	0.37	0
Buffer (million kg)	0.010	0.010	0.009	0.010	0	0
Precipitation (million kg)	0.13	0.14	0.13	0.14	0.14	0.14
Total Dry Solids (million kg)#	5.05	5.56	4.89	6.01	5.02	5.64
Total Water (million kg)	4.34	1.95	3.81	2.38	2.34	2.02

*Additions: s= anaerobic digester sludge; b=buffer (calcium carbonate), approximately 9070 kg; w = water, 1700 m^3;(w) = water, 235-238 m^3; r=recirculation of leachate.

#Excluding Buffer which equaled approximately 9070 kg

to other cells) was low in the beginning and lowest at the end of the study period. Cell A (with partial leachate recirculation) had the highest moisture content at the end of the study period, yet produced less gas then Cell C (Cell C was identical to Cell A except without leachate recirculation). But leachate recirculation resulted in faster stabilization as indicated by volatile solids content, cellulose content, carbon-to-nitrogen ratios, and carbon-to-phosphorus ratios presented in Table 4-5.
There were discrepancies between measured and calculated gas production rates (based on loss of volatile acids). Except for Cell D, which had negligible infiltration, the measured gas production rates for all the other cells were less than calculated values. Cells A and B with highest water infiltration had lowest measured gas production rates. Calculated gas production values indicated that high moisture content (and possibly leachate recirculation) and the addition of sludge increased methane production. Inconsistencies in gas production data were attributed to gas leakage from test cells.

On the basis of refuse analysis from cells A, B, D and F, the following conclusions were made.

- Cells with higher moisture content, sludge addition, less settlement and lower internal temperatures had lower measured gàs production rates.

- The calculated average yearly methane gas production rates based on loss of volatile solids indicated that a higher moisture content, addition of sludge and leachate

Table 4-4. Cell Construction Characteristics and Monitoring Results (1597 Days), Mountain View (Pacey, et al, 1987)

Cell Component	Cell A	Cell B	Cell C	Cell D	Cell E	Cell F
Additions#	sbrw	sb	sbw	b(w)	s(w)	none
Moisture Content at Construction (%)†	46	32	44	28	32	26
Moisture Content at Conclusion (%)	69	54	50	33	45	40
Specific Landfill Gas Yield (m^3/dry kg)	0.08	0.07	0.09	0.16	0.07	0.14
Specific Methane Yield (m^3/dry kg)	0.04	0.04	0.05	0.09	0.04	0.08
Conversion (% of ultimate)‡	19	17	22	40	16	33
Average Gas Production Rate (m^3 /dry kg)	0.02	0.02	0.02	0.04	0.02	0.03
Total Landfill Gas Produced (thousand m^3)	314	275	334	748	238	631
Average Cell Settlement (m)	2.0	2.2	2.3	1.3	2.3	1.9

#Additions: s= anaerobic digester sludge; b=buffer (calcium carbonate), approximately 9070 kg; w = water, 1700 m^3;(w) = water, 235-238 m^3; r=recirculation of leachate.

†After water addition.

‡Calculated ultimate yield = 0.23 m^3 methane/dry kg refuse.

Table 4-5. Refuse Chemical Analysis Summary, Mountain View (Pacey, et al, 1987)

	Cell* A	Cell* B	Cell* D	Cell* F
Sampling interval (m)	0-7.6	0-8.5	0-9.8	0-11.9
Moisture Content (%, wet weight basis)	68.6	54.1	33.3	40.0
Volatile Solids Content(%)	31.8	43.1	50.7	43.5
Cellulose (%)	16.3	25.6	32.8	26.6
Lignin(%)	13.4	14.0	13.6	14.2
Carbon to Nitrogen ratio	13:1	20:1	26:1	27:1
Carbon to Phosphorus ratio	6593:1	945:1	1345:1	1169:1

*Samples were not obtained from Cells C and E

Note: All parameters except moisture content measured on dry basis recirculation enhanced methane gas generation which is in contradiction to measured data. The contradiction was attributed to gas leaks and water infiltration.

- The relationship between moisture infiltration and measured gas production rates (i.e., cells with higher infiltration had lower measured gas production rates) suggests that the pathways of moisture infiltration and gas escape might have been the same.

Binghamton, New York (New York State Energy Research and Development Authority, 1987)
This study conducted for the New York State Energy Research and Development Authority (NYSERDA) was one of the first pilot-scale experiments to investigate the enhancement of landfill gas production by leachate recirculation. The objective of the study was to examine landfill gas production while varying the key parameters controlling anaerobic digestion, namely, moisture content, pH, temperature, and nutrients. Nutrients were controlled by varying the quantity of wastewater treatment plant sludge added to the waste. The pH was controlled by the addition of buffers.

Nine pilot-scale Polyvinyl Chloride (PVC)-lined landfill cells (designated Cell No. 1 through Cell No. 9), 6.4-m (21-ft) deep with 17 m (57 ft) by 23 m (75 ft) foot print, were set up at Nanticoke Landfill, Binghamton, New York. Each cell was equipped with leachate collection, leachate/moisture distribution, and gas collection and metering systems. The first cell was a control cell, the second cell received moisture only (no addition of sludge or buffer), and the third cell received moisture and buffer (lime). The fourth cell received anaerobically digested sludge but no buffer or water. The remaining three cells received both sludge and buffer in varying amounts. Each cell was an encapsulated system separated from other cells. Although nine cells were constructed, only seven were operated. (Cell No. 7 and Cell No. 8 were not operated). The cells were monitored for a period of two years.

Based on gas monitoring data, it was clear that the cells with sewage sludge yielded significantly higher quantities of gas than the cells without sewage sludge. Also, the methane content was higher in the cells with sludge than the cells without sludge. Table 4-6 present data on cell composition; Table 4-7 provides leachate quality data and gas production.

Leachate quality in high gas yielding cells (Cells 4, 5, and 6) was better (lower in strength with respect to COD, TVA and alkalinity) than the low gas yielding cells (Cells 1, 2, 3 and 9). The temperatures remained fairly constant throughout the monitoring period, averaging 10°C in all the cases. Test Cells 2 and 3 with no sludge maintained acidic conditions. Buffer addition was concluded to be ineffective in controlling pH due to short circuiting of leachate.

From the study, it was concluded that addition of sewage sludge (at a rate of 0.45 kg per 115 to 160 kg of municipal solid waste) and leachate recirculation resulted in improved gas production, gas quality, and leachate quality. However, the study also encountered several problems during

Table 4-6. Cell Composition Data, Binghamton, New York (NYSERDA, 1987)

Parameter	Test Cell						
	1	2	3	4	5	6	9
Refuse (Mg)	8.7	7.4	6.98	6.12	6.48	7.89	7.85
Sludge (m^3)	00	0	0	114	91	91	23
Water (m^3)	0	114	114	0	0	0	0
Lime Buffer (kg)	0	0	6800	0	6800	6800	6800
Condition	Control	Leachate Recycle	Leachate Recycle	Leachate Recycle	Leachate Recycle	Leachate Recycle	Leachate Recycle

Table 4-7. Leachate Quality Data from Day 350 to Day 600, Binghamton, New York (NYSERDA, 1987)

Parameter	Test Cell						
	1	2	3	4	5	6	9
TS (%)	0.16	0.54	0.44	0.11	0.10	0.23	0.05
TVS (% of TS)	7.5	48.2	41.2	32.5	33.1	36.6	29.8
COD (mg/l)	780	1,980	1,670	180	200	80	500
TVA (mg/l)	1,120	4,310	4,310	200	270	380	160
Alk(mg/l as $CaCO_3$)	130	1,460	1,750	825	650	2,130	225
pH	6.3	5.9	6.3	6.6	6.6	6.6	6.6
Avg. Gas production (m^3/d)	0.63	0.27	0.21	4.96	5.89	4.96	0.59
Avg. % CH_4	43.4	12.8	33.3	58.9	58.4	56.0	41.1
Normalized gas production ($m^3/d/kg$ MSW x 10^{-6})	0.318	0.046	0.10	4.81	5.31	3.50	0.312
SC (mhos/cm)	660	2,930	2,160	1,510	1,850	2,890	490

TS=Total solids TVA=Total Volatile Acids
TVS=Total Volatile Solids Alk=Alkalinity
COD=Chemical Oxygen Demand SC=Specific Conductance

its operation, including an inability to accurately measure gas quantities and distribute the recirculated leachate throughout the cells, water traps in gas lines due to settlement, and problems due to freezing of pipelines.

Breitenau Landfill, Austria (Lechner, et al, 1993)
The Water Quality Institute of Vienna University of Technology and Waste Management Institute of Geology jointly conducted a pilot-scale research study on the reactor landfill starting in 1986. Three test cells, 17 m (5.2 ft) deep with 2929 m^2 (272 ft^2), 3798 m^2 (353 ft^2), and 4622 m^2 (429 ft^2) foot prints were constructed at the Breitenau Research Landfill, Austria and completely filled with 35 million kg (39,000 tons), 25.6 million kg (28,000 tons), and 33.2 million kg (37,000 tons) of MSW, respectively. The cells were controlled and operated with special attention to moisture content, waste homogeneity, and leachate recirculation such that the landfill cells served as bioreactors. Test Cell 1 served as a control, Test Cell 2 received leachate recirculation, and Test Cell 3 was filled with shredded refuse and received leachate recirculation.

It was observed that within a year of completion of the cells, both liquid and gaseous emissions from the cells dropped drastically. The degradation process in the landfill was observed to have followed the characteristic phases of a typical anaerobic reactor, namely, hydrolysis, acidification, methane formation, and maturation. Table 4-8 presents the average yearly leachate quality data for Test Cell 2 from 1988 to 1991 which shows a steady decrease in leachate strength. The period of decreasing leachate strength coincided with the period of steady gas production.

From the study it was concluded that under suitable operating conditions, the anaerobic degradation process could be accelerated with significant reduction in methane fermentation time. Some of the shortcomings of bioreactor operation observed were: production and escape of gas prior to completion of landfill, leachate ponding, and leachate toxicity due to high ammonium content.

Brogborough, United Kingdom (Campbell, 1991)
The purpose of the Brogborough Test Cell Project was to assess the various field techniques for enhancing landfill gas production. Six test cells were constructed (approximately 40 m (12 ft) by 25 m (7.6 ft)) adjacent to each other and separated by thick clay walls. Each cell was 20 m (6 ft) deep and filled with 15 to 20,000 metric tons (16 to 22 tons) of waste. Wastes were placed in lifts of 2 m (6.5 ft). Variables investigated were waste density and placement, waste composition, sewage sludge, leachate recirculation, and waste temperature in Cells 2 through 6, respectively. Cell 1 was the control cell. These variables were chosen for investigation because of their proven benefits and potential for incorporation into full-scale landfill sites. Cell configuration is summarized below:

- Cell 1 - control, thin layer construction (waste placed in thin layers up to 2 m (6.5 ft)

- Cell 2 - thick waste placement

Table 4-8. Leachate Quality Data for Test Cell 2, Breitenau, Austria (Lechner, et al, 1993)

Month/ Year	COD (mg/l)	BOD_5 (mg/l)	N (org) (mg/l)	NH_3-N (mg/l)	P (total) (mg/l)	Calcium (mg/l)	pH
Nov. 1987	8200	-	200	125	2.0	1200	6.6
Mar. 1988	27000	16500	720	600	3.2	2300	6.2
Nov. 1988	4300	930	1900	1600	6.4	35	8.3
Mar. 1989	3800	770	2100	1850	9.2	30	7.9
Nov. 1989	2200	130	1300	1150	3.6	33	8.1
Mar. 1990	2650	190	1650	1550	7.2	20	7.7
Nov. 1990	1000	70	630	580	2.8	60	8.0
Mar. 1991	900	38	630	420	2.8	43	8.1
Nov. 1991	660	36	500	440	2.0	55	8.3
Feb. 1992	770	21	550	440	2.0	44	8.2

- Cell 3 - leachate recirculation
- Cell 4 - air injection for temperature control
- Cell 5 - sewage sludge addition

Results indicated that a significant quantity of gas was produced within two years of initial deposition of waste. A mixture of nonhazardous industrial and commercial waste with domestic waste appeared to promote more efficient degradation based on gas production. Settlement was found to significantly impact the integrity of the cap and gas recovery piping. Based on the monitoring data of the test cells, the following preliminary conclusions were made.

- Gas production rates were in close agreement with theoretical expectations of 5.5 to 11.0 m^3/ metric t/year (170 to 350 ft^3/ton/year).
- Sewage sludge increased gas yield and quality.
- Mixed wastes enhanced gas production.
- The leachate-recirculated cell degraded organic matter faster as indicated by a significant decrease in TOC compared to other cells.

SORAB Test Cells (Brundin, 1991)
A series of test cells, also known as Energy Loaves, were constructed on an annual basis from 1989 through 1991 at the Hagby Landfill Site in Taby, Stockholm, Sweden. The investigators used a natural digester-type reactor in order to optimize parameters controlling digestion, to minimize degradation time, evaluate gas extraction devices, investigate processing of residuals, and characterize residuals. The first Energy Loaf was 90 m (295 ft) long, 40 m (130 ft) wide, and 6 m (20 ft) high, and filled with 8200 metric tons (9000 tons) of crushed solid waste overlaid with 30 cm (1 ft) of peat for insulation. Leachate recirculation was practiced to maintain an optimum moisture content and heat the system to 35 to 40°C. Landfill gas-fueled boilers were used to heat the leachate. Gas production was reported to be an order of magnitude higher than typical. Problems were encountered with water filling vertical gas extraction wells. A later Energy Loaf employed horizontal gas collection and leachate distribution pipes.

Full-Scale Landfill Bioreactor Studies

Lycoming County, Pennsylvania (Natale and Anderson, 1985)
Lycoming County Landfill is located 15.3 km (9.5 miles) South of Williamsport, Pennsylvania and is operated by the Lycoming County Solid Waste Department. This 53-hectare (130-acre) landfill facility serves Lycoming and other neighboring counties for a total population of 325,000. The initial fill area for Fields I, II and III was 13 hectares (31 acres) and development of additional fields has occurred when needed. The landfill operations began in June 1978, and the site is projected to be active through 2013, based on current landfilling rates. The landfill consists of six fields numbered 1 through 6, all of them lined with PVC, the newer fields having thicker and improved liner systems. Leachate recirculation was investigated over a seven-year period.

Leachate Management Facilities
The original leachate management techniques included collection, storage, recirculation, and off-site hauling. The liner system (in addition to the site's natural features of a mantle of compacted glacial till and low permeability bed rock) consists of:

- a 30-cm (1-ft) thick sand layer containing underdrainage collection system,
- a PVC membrane liner (single 0.05-cm (20-mil) liner for Fields 1, 2 and 3; 0.076-cm (30-mil) liner for field 4 and 0.076- and 0.13-cm (30- and 50-mil) liners for field 5),
- a 15-cm (0.5-ft) sand layer containing leachate collection system piping network,
- a 30-cm (1-ft) clay layer.

The leachate collection system consists of a series of 15-cm and 20-cm (6-in and 8-in) diameter perforated collection pipes placed in the sand layer on top of the PVC liner. The leachate collection system transports the leachate to the equalization lagoon. The PVC-lined leachate equalization lagoon with a permitted capacity of 4500 m^3 (160,000 ft^3) is equipped with floating aerators to keep the solids in suspension, prevent excessive odors, and provide aeration. The lagoon, from which the leachate is recirculated, also had a freeboard to handle leachate in case of emergency. Gas vents, consisting of 15-cm (6-in) diameter PVC piping in gravel-packed 1.2-m (4-ft) diameter concrete cylinders, are also provided.

Leachate Recirculation Techniques

Various techniques of leachate recirculation were tried to achieve effective distribution of leachate. Originally, it was planned to spray leachate on the operating face and other areas using spray headers. Spraying on the working face using a spray nozzle was also tried which allowed for flexibility in operation but was labor intensive and cumbersome. Spraying also caused odor problems to landfill operators and equipment. The next technique tried was to excavate small pits in the waste and fill them with leachate using a spray header. Due to the shallow depth of the landfill, the waste had limited absorption capacity and the technique was abandoned.

To increase recirculation volumes, another technique was tried incorporating trenches. Trenches were excavated on the completed sections of the landfill and filled with leachate. The absorption capacity of the trenches varied and resulted in leachate outbreaks in some parts of the landfill. Leachate outbreaks continued to occur and coincided with periods of peak infiltration and recirculation. The trench method was modified by filling the trench with auto-shredding derived waste or baled fiberglass wastes. These materials acted as wicks and transferred leachate to a larger area of the refuse thereby increasing the allowable recirculation volumes and permitting longer use of trenches. A combination of these techniques was also used. Bale-filled areas were connected to a auto waste-filled trench. An injection well was also installed in the bale-filled area using perforated concrete well rings. However, the impact of auto-shredding waste and fiberglass waste on leachate quality was not known.

Leachate Quantities

It was anticipated that due to absorption of moisture by the new waste, leachate generation would not occur until 16 to 22 years after the start of landfilling operations. However, leachate began to flow into the storage lagoon less than seven months after waste disposal began. Several factors were thought to account for the early arrival of leachate including lower waste volumes (less than design) leading to less leachate absorption, leachate channeling (resulting in inefficient absorption) and a large open area collecting precipitation. Also, the climate is humid with annual average precipitation exceeding evaporation.

Within three years of landfill opening (1978), the leachate level in the equalization lagoon rose above its permitted level twice. The situations were handled by increasing recirculation quantities. Off-site hauling was started in 1982 after it was clear that leachate management by recirculation alone was not possible using the existing leachate lagoon. The lagoon also collected a significant quantity of precipitation, approximately 20,100 m^3 per year (5.3 MG/year) between January 1980 and December 1982. Consulting engineers for the facility made recommendations for the effective management of leachate which included construction of a second storage lagoon and negotiation for leachate disposal contracts with a local wastewater treatment facility.

The data on leachate quantity were from different sources including daily logs, monthly reports, planning documents, summary sheets and reports from the National Oceanic and Atmospheric (NOAA) weather station at Williamsport. The leachate quantity data included precipitation data, leachate flow measurements, lagoon level records, leachate recirculation pump records, and leachate hauling and treatment records. Although the reliability and accuracy of each source of data varies considerably, the data yield valuable information on the leachate quantities involved. The volumes of recirculation based on four sources (daily logs, monthly reports, summary sheets, and planning documents) and different pumping capacity factors were sometimes conflicting. The average recirculation rate was 24 m^3/hr (100 gpm) based on the engineer's report and 27 m^3/hr (120 gpm) based on summary sheets for the period November 1979 through April 1981. The total quantity of leachate recirculated was around 24,600 m^3 (6.5 MG) between November 1979 and January 1981. Over the first three years, over 49,200 m^3 (13 MG) of leachate were recirculated. Recirculation rates approaching 3800 m^3 (1 MG) per month and 19,000 m^3 (5 MG) per year were recorded at the landfill. The average monthly volume of leachate hauled off-site was about 760 m^3 (200,000 gal) for the period of March 1982 to June 1985.

The leachate generation quantities were estimated using a water balance method and compared with quantities derived from the lagoon balance for Field 1 for the year 1982. The water balance method estimate of 7300 m^3 (2 MG) compared well with 6800 m^3 (1.8 MG) derived from a lagoon balance and 8400 m^3 (2.2 MG) of measured inflow into the lagoon.

It was estimated that the moisture storage capacity of the solid waste was not fully utilized and was verified by excavations which revealed dry cells which were previously considered to be at field capacity. The estimated breakdown of a water budget as of December 31, 1984 is provided in Table 4-9.

Thus, excess or unutilized moisture storage capacity was 7,600 to 45,000 m^3 (2 to 12 MG). The quantity of moisture storage capacity rendered unavailable due to clayey daily cover and cell configuration being impossible to estimate, the net available moisture storage capacity was estimated to be between zero and 38,000 m^3 (0 to 10 MG) as of December 31, 1984.

Leachate Quality

Samples of leachate were collected quarterly (beginning six months after landfilling commenced) and analyzed for approximately 20 parameters; 45 parameters were analyzed annually. Composite samples were taken from the lagoon through December 1979 following which grab samples were collected, typically from near the end of the leachate discharge pipe, representing raw leachate quality.

Table 4-9. Water Budget Lycoming County (Natale and Anderson, 1985)

Moisture Source	Volume, m^3
Percolation (1978-1984)	+121,100
Sludge water (1978 - 1984	+49,200
Off-site hauling (1984 - 1984)	-26,500
Net utilized moisture storage capacity	143,800
Solid waste moisture storage capacity	151,400 to 189,300

Like all leachate, the quality was highly variable, generally falling within the range reported in literature sources. The values of specific conductance, volatile acids, and manganese exceeded the upper limit of the typical ranges. The occurrence of manganese in the site soil is responsible for the high manganese content. The values of total solids, calcium, chloride and phosphate were below the lower limit of typical minimum values. The ratios of COD/TOC and BOD/COD, indicative of the age of leachate, placed the leachate in an early stage (less than five years) of landfilling when compared to typical ratios. The values of some of the key raw leachate parameters are shown in Table 4-10.

The samples were collected from each tanker whenever leachate was hauled for treatment offsite, representing leachate effluent quality. The lagoon effluent quality was less variable than raw leachate due to equalization, sedimentation, biological treatment, aeration, and dilution (due to precipitation). The lagoon effluent quality between March 1982 and January 1985 is summarized in the Table 4-11.

Gas Production

Based on the analyses of borings, samples, and mathematical modeling performed in 1983, it was concluded that:

- Field 1 was producing methane gas at a rate of 9910 m^3 (350,000 ft^3) CH_4/day (as of 1983), twice as much as a landfill without leachate recirculation.
- Significant gas production began in Field 1 in 1981 coincident with a sharp decline in COD and TVA and steep increase in pH.
- As of 1983, over 40 percent of methane generation capacity was exhausted in Field 1.
- Field 2 was producing methane at a rate of 10,200 m^3 (360,000 ft^3) CH_4/day (as of 1983) and was projected to increase to 22,400 m^3 (790,000 ft^3) CH_4/day in five years.

Table 4-10. Leachate Parameter Values, Lycoming County (Natale and Anderson, 1985)*

Parameter	No. of tests	Min. (1978-1985)	Max. (1978-1985)	Avg. (1978-1985)	Avg. (1981-1985)	Range
pH	27	5.8	8.6	7.0	7.2	4.7-8.8
Alkalinity	27	404	8,300	3,100	2,400	140-9,650
BOD_5	26	681	28,000	7,300	5,00	4-57,700
COD	27	475	29,947	10,000	7,300	31-71,700
TOC	19	350	8,500	3,200	2,500	0-18,800
Total solids	27	1298	23,210	9,300	7,100	1,460-55,300
Volatile Acids	19	223	30,730	6,600	4,000	70-27,700
Total Nitrogen	10	100.3	478.5	230	140	7-1,970
Total Phosphorus	10	0.03	7.2	1.0	0.46	0.2-120
Iron	27	19.5	1,095	280	230	4-2,200
Chloride	27	13	1,854	880	710	30-5,000

*All units in mg/l except for pH

Table 4-11. Lagoon Effluent Quality Lycoming County (Natale and Anderson, 1985)*

Parameter	No. of Tests	Min.	Max.	Avg.
pH	53	6.74	8.51	7.8
Alkalinity	2	1,020	1,054	1,037
BOD_5	54	608	4,066	2,000
COD	53	1,400	5,000	3,100
Total Solids	3	3,138	4,019	3,700
Total Nitrogen	4	112.1	164.4	130
Total Phosphates	7	BDL	2	1
Iron	31	19.08	161.5	56

*all units are in mg/l except for pH
BDL - below detection limit

Settlement

There was no measurable settlement at the landfill. The excavations and backfilling activities, relatively shallow depth of the landfill (less than 21 m (69 ft) at the deepest point), large amount of daily cover (limiting the settlement), stockpiling of cover materials, and absence of settlement plates may have obscured settlement detection. Settlement would extend the life of the landfill because the final site development is limited by elevation and not by volume or quantity. Thus, settlement allows additional waste to be placed on completed areas.

Conclusions

Based on the performance evaluation for the Lycoming County Landfill, the following conclusions were made.

- Waste degradation and methane generation were improved as a result of leachate recirculation.
- Quality of leachate stabilized more rapidly than landfills without leachate recirculation.
- Stabilization rates close to pilot-scale studies (with low recirculation rates and minimum daily cover) can be achieved.
- Clayey cover soil, high recirculation rates, and certain industrial residuals may inhibit the vertical flow of leachate resulting in incomplete use of moisture storage capacity as well as ponding within the landfill.
- The operational practices and design features for recirculation were adequate but their effectiveness could be improved.
- The major potential adverse impact of leachate recirculation involved leachate pollutant releases through irrigation drift and stormwater runoff.
- The leachate recirculation methods used were labor intensive and cumbersome although effective (injection well method being the most effective).
- Because of an inability to isolate storm water collecting on unutilized areas of the landfill from the leachate collection system, these areas generated significant quantities of leachate.
- Aerated leachate storage lagoons provided effective pretreatment of raw leachate.
- Leachate should be recirculated sufficiently to utilize moisture storage capacity rather than saturating the landfill which can lead to leachate outbreaks.

Seamer Car Landfill, United Kingdom (Barber and Maris, 1984)
The potential benefits of leachate recirculation including reduction of leachate volume (due to evaporation), reduction of leachate strength, rapid stabilization of wastes and enhanced gas production were confirmed by lysimeter and pilot scale studies reported by Barber and Maris (1984). The Seamer Car landfill investigation, initiated in 1979, was intended to determine the practicalities of leachate recirculation at full-scale landfill sites. The 2-ha site (5-acre), lined with a 0.3-cm (118-mil) HDPE, was filled with pulverized domestic waste placed at a density of 800 to 990 kg/m^3 (1350 to 1680 lb/yd^3). An area of one hectare (2.5 acres) was subjected to leachate recirculation by spraying, while the remaining one hectare served as the control area. Measured volumes of leachate were recirculated beginning in August 1980. Approximately 300 m^3 (79,000 gal) of leachate were recirculated for five months in 1980, 3780 m^3 (1 MG) and 11,400 m^3 3 MG) in 1981 and 1982, respectively, were recirculated.

Surface furrowing was found to reduce runoff and ponding problems in addition to increasing the infiltration rate significantly. The low permeability intermediate cover caused zones of saturation and lateral movement of leachate. Perched water table had developed within the recirculation area as determined by borehole investigations. All leachate was managed on-site over a three-year period, however landfill saturation eventually made off-site disposal necessary. The following conclusions were made from the investigations.

- Although longer times were required than laboratory-scale studies indicated, laboratory-scale benefits could be obtained at full-scale landfills.
- Regular surface furrowing alleviated surface ponding problems.
- Intermediate cover resulted in perched water table and lateral seepage of leachate.
- Rapid reduction in leachate organic strength was achieved by increasing the waste moisture content.
- Residual COD, ammonia, and chloride concentration in leachate suggest that further treatment/dilution would be necessary prior to final disposal.

Delaware Solid Waste Authority (Watson, 1993)
The Delaware Solid Waste Authority (DSWA) operates three landfills in New Castle, Kent, and Sussex counties in Delaware. The Central Solid Waste Management Center (CSWMC) in Sandtown, Kent County, Delaware began operations in October 1980 and has five sections, designated Areas A through E (Area E is actually two 0.4-hectare (1-acre) test cells). All of the cells are lined and equipped with leachate collection and recirculation facilities (except one of the test cells which does not have recirculation capabilities).

Leachate recirculation is applied to all the cells (excluding on of the test cells) and has been identified as one of the means (the other being landfill reclamation) of achieving the Authority's objective of maximizing the reduction, reuse, recycling, and resource recovery of solid waste and minimizing landfilling. The Authority refers to the term "Active Landfill Management" to include the basic features of leachate recirculation and landfill reclamation.

At CSWMC, leachate recirculation has been accomplished by various methods including vertical recharge wells, spray irrigation systems, and surface application. Recirculation by recharge wells was found to be simplest and most affective. The recharge rate for the wells ranged from 76 to 760 l/min (20 to 200 gpm). Spray irrigation, the second preferred option, was accomplished using traveling spray irrigators with a capacity of 380 l/min (100 gpm), 30-m (100-ft) spray radius, and maximum travel distance of 210 m (680 ft). Evaporation rates of over 30 percent were measured at CSWMC.

The total quantities of leachate generated and recirculated annually at CSWMC are shown in Table 4-12. The fill has been constructed in three stages in Areas A, B, and C with areas of 3.6, 7.3, and 8.1 hectares (8.8, 18, and 20 acres), respectively. At closure, trenches equipped with infiltrators are installed under the cap. The newest 8.9-ha (22-acre) cell (Area D) is double-lined including a 0.15-

Table 4-12. Total Quantities of Leachate Generated and Recirculated Annually, Delaware Solid Waste Authority (Watson, 1993)*

Year	Generated, m^3	Recirculated, m^3	Treated, m^3
1981	0	0	0
1982	2080	0	0
1983	8540	114	7600
1984	8540	117	7600
1985	5200	132	0
1986	7410	16300	0
1987	10600	10600	0
1988	12800	12800	0
1989	24200	19000	5200
1990	26800	13300	13500
1991	29500	13500	16000
1992	24600	8200	16400

cm (60-mil) geosynthetic/clay composite and 0.15-cm (60-mil) HDPE liner. Leachate recirculation will be accomplished using vertical wells followed by trenches at closure. In Areas A and B, the quantity of leachate generated declined as the quantity of leachate recirculated decreased. However, the quantity of leachate treated off-site was substantial. In the case of Area C, a large portion of leachate generated was recirculated resulting in a decrease in the quantity of leachate treated off-site.

Table 4-13 shows leachate quality data for Area B over a period of ten years. Rapid decline in the organic strength of leachate, enhanced by leachate recirculation, was observed after closure in late 1988. Areas A, B, and C generated gas early during the operating period and the composition was observed to be 55 percent methane and 45 percent carbon dioxide. Unfortunately, no gas generation rates are available.

Table 4-13. Leachate Quality Data for Area B, DSWA (Watson, 1993)*

	Sep. 1983	Mar. 1984	Jan. 1985	Jan. 1986	Jan. 1987	Jan. 1988	Jan. 1989	Jan. 1990	Jan. 1991	Jan. 1992	Jan. 1992
pH	5.39	7.00	5.7	5.74	5.75	6.15	6.75	6.80	7.16	7.16	7.39
COD	20,000	120	29,893	30,000	34,556	28,300	15,500	5,620	1,775	1,800	1,000
BOD	1,773	76	17,300	20,250	25,750	20,500	12,591	1,144	352	540	50
TOC	6,170	25	NA	10,000	10,000	1,900	4,950	1,178	238	540	290
TDS	NA	NA	14,800	18,600	15,999	14,713	6,558	7,726	6,497	5,100	4,900
TSS	39	19	965	137	NA	NA	1,558	502	413	170	50
Chloride	NA	NA	1,440	NA	1,500	1,683	925	1,450	650	1,100	1,200
Iron	NA	NA	972	1,050	672	1,005	596	116	104	70	12
AA#	NA	NA	203	NA	6,200	4,570	4,030	1,370	390	210	NA

*All quantities in mg/l except pH.
#Acetic acid
NA - data not available

The capital cost of leachate recirculation systems (for pumping stations and piping network) constructed by DSWA ranged from $10,000 to $200,000 (1993 dollars) which is significantly less than the cost of a leachate treatment plant, presently being considered by DSWA, and estimated between $1,000,000 and $6,000,000. The Authority found leachate recirculation to be the most economical way of handling leachate apart from the benefits of accelerated biodegradation and reduced long-term risks to the environment.

Based on the performance evaluation of leachate recirculating landfills, the Delaware Solid Waste Authority has successfully demonstrated that leachate recirculation results in many benefits including:

- inexpensive leachate treatment,

- accelerated biodegradation of organic portion of the waste,
- reduced long-term risk to the environment, and
- increased production of landfill gas.

German Experiences (Doedens and Cord-Landwehr, 1989)
In the former Federal Republic of Germany (now unified Germany), thirteen landfills were practicing leachate recirculation in 1981 using spray irrigation, spray tankers, and horizontal distribution pipes. These sites varied in size from two to 12 hectares (5 to 30 acres). For those landfills using spray irrigation, an average of 0.5 m^3/ha/d (50 gal/acre/d) of excess leachate were produced; 2 m^3/ha/d (200 gal/acre/d) were produced from those sites using surface percolation, and 4 to 5 m^3/ha/d (400 to 500 gal/acre/d) were produced from conventional landfills without leachate recirculation. Large storage volumes (1500 to 2000 m^3/ha (160,000 to 210,000 gal/acre)) were recommended.

It was observed that landfills practicing leachate recirculation since the commencement of landfill operations demonstrated a faster reduction of BOD and COD than landfills beginning leachate recirculation several years after the commencement of landfilling operation. Also, all of the landfills practicing leachate recirculation had a BOD of 1000 mg/L or less and a COD of 10,000 mg/L or less, four years after the start of landfilling operations. No increase in the concentrations of salts or heavy metals attributable to leachate recirculation was observed. Landfills where waste was placed in thin-layers (1.8-m (6-ft) thickness) were observed to have very low strength leachate.

Bornhausen Landfill, Germany (Doedens and Cord-Landwehr, 1989)
Stegman and Spendling (1989) suggested that a combination of thin layer waste placement and leachate recirculation resulted in faster waste degradation and consequently faster reduction in BOD and COD concentrations in the leachate. Waste is placed in thin layers of up to 2 m (6 ft) and loosely compacted as opposed to rapid vertical filling. Thin layers promotes natural ventilation and aerobic decomposition. Penetration of oxygen into the landfill (up to 0.9 m (3 ft) depending on the density of the waste) was documented. Experiments were conducted at the Bornhausen landfill, Germany, to study the thin layer process suggested by Stegman and Spendling.

Three test sites were set up with leachate recirculation. Approximately 600 m^3 (21,000 ft^3) waste were placed in 4-m (13-ft) layers during a period of six months. The following results were obtained.

- No increase in leachate concentration was observed after leachate recirculation was started. After 350 to 450 days, COD was less than 4000 mg/L and BOD was less than 1000 mg/L for all the test sites.
- The "thin layer" operation coupled with natural ventilation up through the drainage layer proved to be more effective than leachate recirculation.

Two other sites of approximately 0.5 hectares (1.2 acres) each at the Bornhausen landfill were constructed in 2.0-m (6.5-ft) layers, one with and the other without leachate recirculation. The time required for stabilization with leachate recirculation (230 days) was half of the site without leachate recirculation (460 days).

Another significant application of leachate recirculation at the Bornhausen landfill involved the introduction of highly concentrated leachate from new landfill cells over older cells in which a stabilized leachate was already being produced. Table 4-14 presents data which demonstrate the removal of BOD and COD by two-stage leachate recirculation (leachate from the new cell recirculated over an old cell). COD and BOD reduction from 90 to 99 percent was achieved, presumably through treatment as the leachate passed through the stabilized waste.

Table 4-14. BOD AND COD Removal by Two-Stage Leachate Recirculation, Bornhausen Landfill (Doedens and Cord-Landwehr, 1989)

Month/Year	COD (mg/l)		BOD (mg/1)	
	New	Old	New	Old
Feb, 1982	-	1473	-	60
Mar, 1982	5303	1278	1310	64
April, 1982	10390	1370	5320	59
Aug, 1982	19308	1273	11970	60
Dec, 1982	4898	1083	1807	82
Feb, 1983	19385	1350	19650	61
May, 1983	19675	1604	9200	173
July, 1983	10780	1364	6387	91
Sept, 1983	10615	927	8750	96
Nov, 1983	21720	1271	12450	39
Dec, 1983	21470	1226	14450	37
Jan, 1984	16425	1725	6450	75

Summary

The studies described in this chapter conclusively demonstrated the advantages of operating the landfill as a bioreactor and provided information necessary to design, construct, and operate the next generation of landfills, some of which are described in Chapter 5. Leachate and gas data from these studies are summarized and analyzed in Chapter 6. Furthermore, information derived from these and other studies provides the basis for design and operating recommendations made in Chapters 7 and 8. For convenience, major project descriptors and conclusions are provided in Table 4-15.

Table 4-15. Summary of Bioreactor Investigations

Location	Dimensions	Enhancement Techniques	Conclusions	Reference
Ga. Institute of Technology	4 columns: 0.9 m diameter, 3 m waste depth	recirculation, pH control, sludge addition	- recirculation with pH control produced low organic strength leachate faster - sludge had no effect	Pohland, 1975
Univ. Louisville	4 columns: 0.9 m diameter, 2.4 m waste depth	recirculation, shredding, pH control, nutrient addition	- recirculation with pH control produced low organic strength leachate faster - shredding and nutrient addition no effect	Tittlebaum, 1982
German Experiment	4 columns: 1.5 m diameter, 1.35 m waste depth	recirculation, initial saturation, vary water input rate	-recirculation reduced the emission of inorganic and organic pollutants -no increase in gas production or quality from enhancement	Doedens and Cord-Landwehr, 1989
Newcastle Univ.	4 lysimeters: 0.5 m diameter	recirculation, shredding, saturation vs. free draining, waste density	- shredding increased rate of degradation - saturation of no benefit - lower density increased rate of waste degradation	Otieno, 1989
Ga. Institute of Technology	10 columns: 0.9-m diameter, 3 m waste depth	recirculation, addition of priority pollutants	-recirculation increased gas volume and rate, decreased leachate organic strength - recirculation promoted attenuation of inorganic and organic pollutants	Pohland, et al, 1992

Table 4-15. Continued.

Location	Dimensions	Enhancement Techniques	Conclusions	Reference
Sonoma County	5 cells: 15mx15mx3m	recirculation, high initial water content, continuous throughput of water, septic tank pumpings addition	- recirculation increased rate of microbial community establishment - recirculation provided in situ leachate treatment	Leckie, et al, 1979
Ga. Institute of Technology	2 cells: 3mx3mx4.3m	recirculation, sealing of cell	-sealed recirculation more conducive to methanogenic conditions than open air cell	Pohland, 1980
Mountain View, Ca.	6 cells: ≈ 10,000 m^2, 14 m deep	recirculation, water addition, buffer, sludge addition	-inconclusive regarding recirculation effects due to gas loss -refuse analyses suggest water addition accelerates degradation	Pacey, 1987
Binghamton, NY	9 cells: 17mx23mx6.4m	recirculation, sludge addition	-recirculation and sludge addition improved gas and leachate quality	NYSERDA, 1987
Breitenau Landfill, Austria	3 cells: 3000 - 4600 m^2, 17 m deep	recirculation, shredding, sludge addition	- anaerobic digestion can be accelerated by enhancements - concerns with ponding and increase in ammonia concentrations	Lechner, et al, 1993
Brogborough, UK	6 cells: 40mx25mx20m	thin layer construction, air injection, mixed waste, sewage sludge addition	-large volumes of gas from cells with sludge and air addition -liquid addition may increase gas production	Campbell, 1991
SORAB Test Cells, Sweden	3 Energy Loaves: 95mx35mx5.5m	leachate heating, recirculation, shredding,	-gas volume order of magnitude greater than ordinary landfills	Brundin, 1991

Table 4-15. Continued.

Location	Dimensions	Enhancement Techniques	Conclusions	Reference
Lycoming, PA	52.6 ha, depth - max 21 m	recirculation: - spray - trenches - injection wells	- recirculation increases rate of waste degradation and methane generation - ponding and saturation lead to leachate outbreaks - injection wells most efficient	Natale and Anderson, 1985
Seamer Car Landfill	2 cells, 1 ha each 4 m deep	recirculation: spray irrigation	- Accelerated decline in leachate organic strength - clayey intermediate cover caused ponding - surface furrowing required	Barber and Maris, 1984
Delaware Solid Waste Authority	5 areas - 3.6 to 8.9 ha	recirculation: - spray - recharge wells - horizontal infiltrators	- recirculation accelerates the biodegradation of wastes - recirculation improved the quality of gas and leachate at low capital cost	Watson, 1993
Bornhauser Landfill, Germany	3 cells: 50 m^2 x 4 m deep 2 cells: 0.6 ha, 2 m deep	recirculation, thin layer compaction	- recirculation cut stabilization time in half	Doedens and Cord-Landwehr, 1989

Chapter 5
Full-Scale Experiences with Bioreactor Landfills - Case Studies

Introduction

From the technical literature, telephone inquiry of state regulators, and contact with the solid waste community, a number of full-scale landfill bioreactors have been identified. These facilities evolved from demonstration projects completed in the late 1970's and early 80's described in Chapter 4 which provided essential information for the planning, design, and operation of new generation facilities. A description of many of these sites is provided below. A summary of leachate management data is provided in Table 5-1.

Southwest Landfill, Alachua County, Florida

The active Alachua County Southwest Landfill is a 10.9-ha (27-acre) composite-lined (0.15-cm (60-mil) HDPE over 30 cm (1 ft) of clay) facility located in north central Florida. Waste was first accepted in the spring of 1988 and the facility continues to receive approximately 900 metric tons (10,000 tons) of MSW per month. Maximum landfill depth will be approximately 20 m (65 ft). The landfill is permitted to recirculate up to 230 m^3/d (60,000 gpd). Leachate drains by gravity through a leachate collection system to a sump and is pumped to four 340-m^3 (90,000-gal) 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 Figure 5-1). A section of the landfill was purposely not exposed to leachate recirculation to provide a comparison to the test area. Over 30 million liters (8 million gal) of leachate were recycled to the landfill through the pond system from 1990 through 1992. Infiltration rates averaged between 5.3 and 7.7 l/m^2/day (0.13 to 0.19 gal/ft^2/day) (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 Figure 5-2). Horizontal pipes have been placed in 2.4-m (8-ft) wide and 120 to 210-m (400 to 700-ft) long trenches filled with tire 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 liters (2 million gal) were pumped to the first two laterals over a period of six weeks (310 to 620 l/day per m of trench (25 to 50 gpd/ft)) at

Table 5-1. Full-Scale Leachate Recirculating Landfill Water Balance Data*

Site	Leachate Production, m^3/ha/d (gal/acre/d)	Leachate Recirculation, m^3/ha/d (gal/acre/d)	External Storage, m^3/ha (gal/acre)	Off Site Treatment, m^3/ha/d (gal/acre/d)	Design Area, ha (acres)	Active Area, ha (acres)
Alachua County	7.8 (837)	4.3 (4602)	124 (13300)	4.3 (460)	11 (27)	11 (27)
Worcester County	2.6 (275)	2.1 (230)	220 (23500)	0.64 (68)	6.9 (17)	6.9 (17)
Winfield County	19 (2000)	14 (1500)	67 (7100)	0.55 (59)	2.8 (7)	2.8 (7)
Pecan Row	2.7 (290)	1.1 (120)	690 (73600)	0	16 (40)	4.5 (11)
Lower Mt. Washington Valley	15 (1600)	9.5 (1000)	12 (1250)	4.2 (450)	3.2 (8)	0.45 (1.1)
CRSWMA	17 (1800)	12 (1200)	1600 (171000)	0	8.9 (22)	5.7 (14)
Lemons	2.2 (240)†	5 (540)	110 (11600)	NA	30 (75)	NA
Mill Seat						
Test Cell 2	2.8 (300)†	6.8 (720)	35 (3700)	NA	2.8 (6.9)	NA
Test Cell 3	2.8 (300)†	5.2 (560)	41 (4300)	NA	2.2 (5.4)	NA

*Based on current operational area

† Estimated Using the Hydrologic Evaluation of Landfill Performance Model, excludes recirculated flow

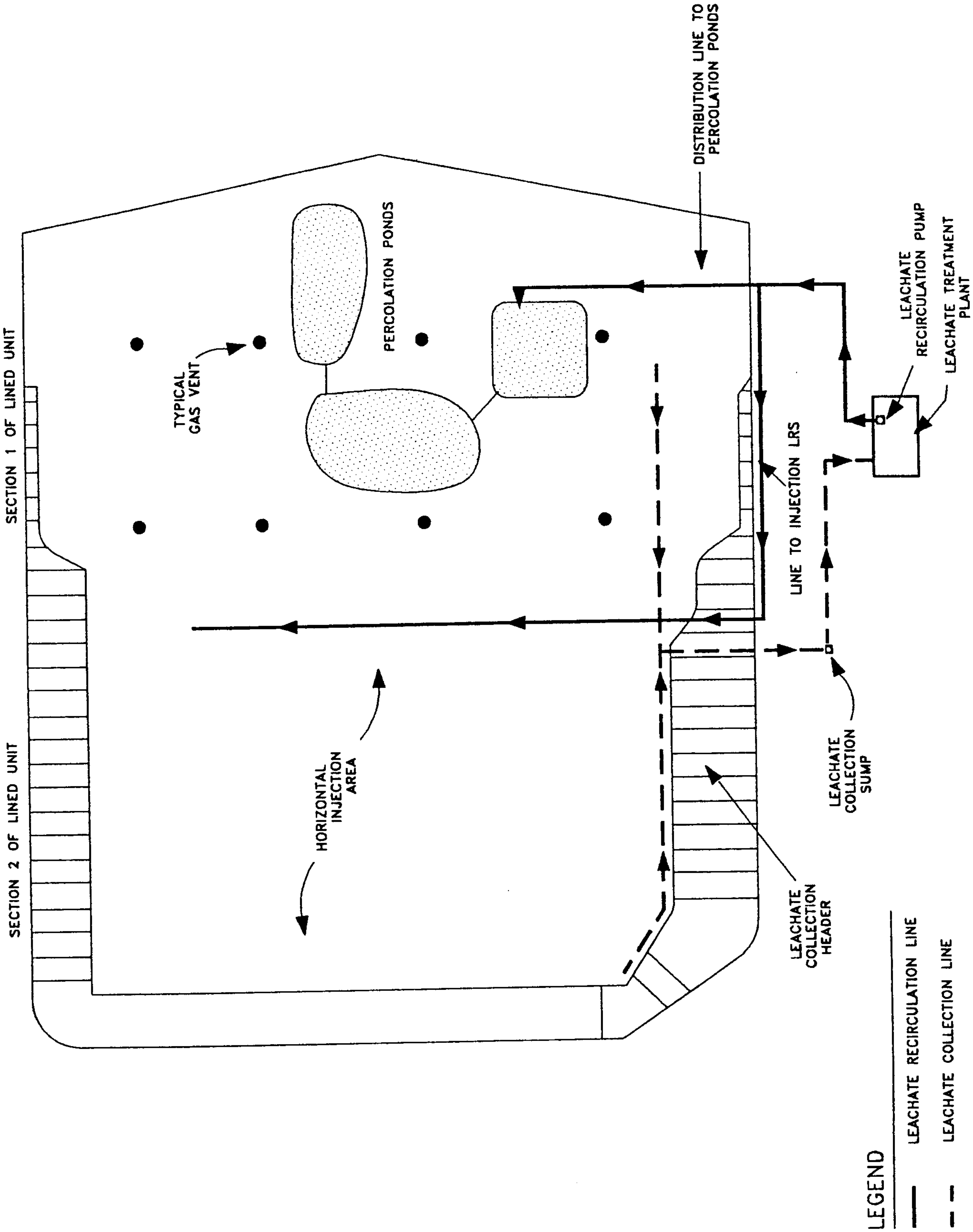


Figure 5-1. Leachate recirculation system, Alachua County, FL Southwest Landfill.

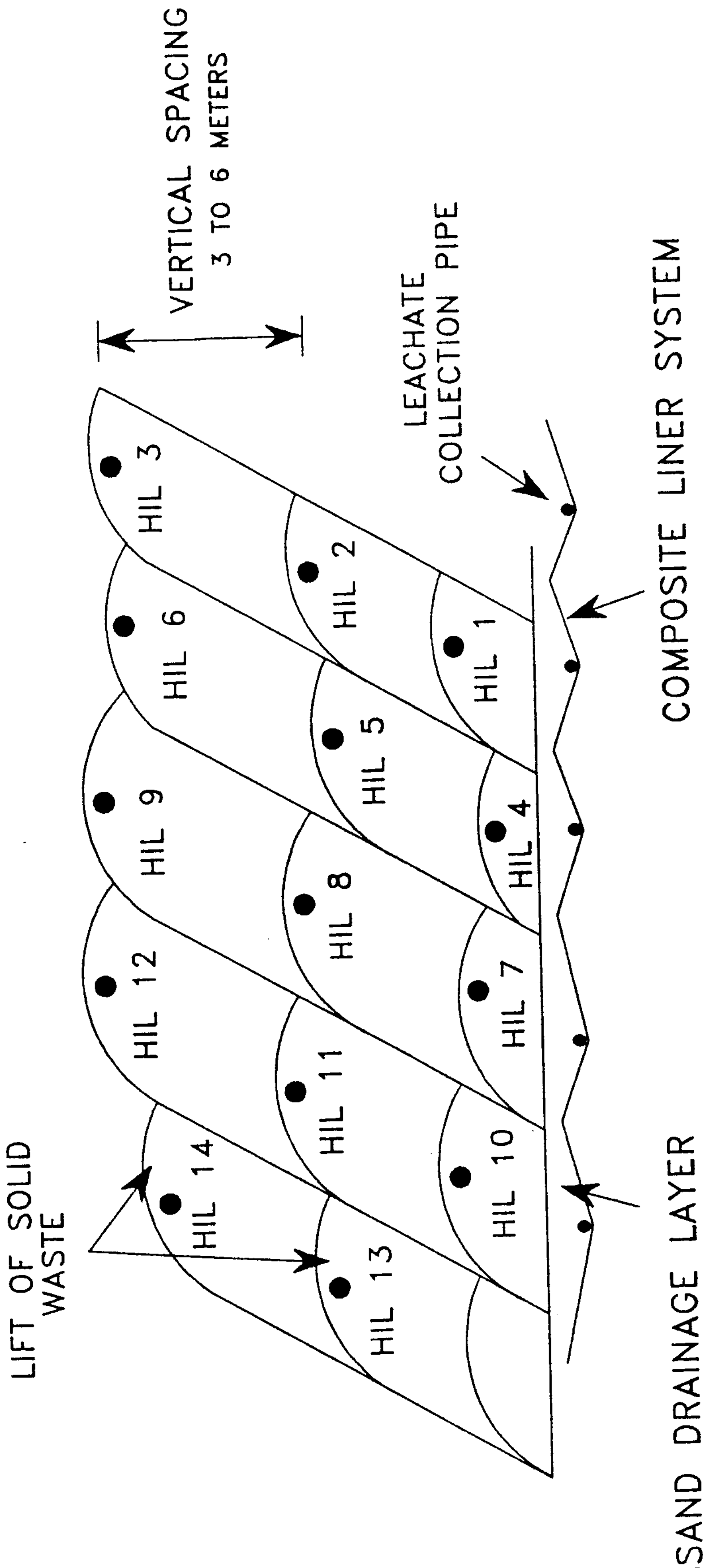


Figure 5-2. Horizontal injection system (HIL), Alachua County, FL Southwest Landfill.

a rate of 230 to 380 lpm (60 to 100 gpm) without experiencing pump discharge pressure exceeding 55 kPa (8 psi). 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, 760 to 3000 m^3/month (200,000 to 780,000 gal/month) 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.

Central Facility Landfill, Worcester County, Maryland

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 (see Figure 5-3). Maximum fill height will be 27 m (90 ft). Waste receipt averages 180 TPD (200 tpd). 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 (6-inch) perforated polyvinyl chloride (PVC) pipes which carry the leachate to sumps located at the four corners of the cell. Leachate is pumped to a 1500-m^3 (400,000 gal) steel storage tank.

Leachate recirculation is accomplished using vertical discharge wells constructed using 1.2-m (four-ft) diameter perforated concrete manhole sections. The first 2.4-m (eight-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 (two-in) PVC standpipe is installed within each well to vent gas and permit monitoring of water depth. A schematic of the vertical well used at the Central Facility Landfill is provided in Figure 5-4. Each well serves a 0.8-ha (two-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 reintroduce leachate. Usually these ponds are constructed around the wells and isolated by berms. Estimated construction costs for recirculation facilities were $26,000 (1989 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.

Winfield Landfill, Columbia County, Florida

The Winfield Landfill located in Columbia County, Florida, opened in September of 1992. The double-liner system provided is composed of a 46-cm (18-in) drainage layer, 0.15-cm (60-mil) HDPE geomembrane, and leachate detection system installed over an 46-cm (18-in) clay soil liner, hydraulic conductivity 10^{-8} cm/sec. 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 (Spring 1995) is 2.8 ha (seven acres) with plans for an ultimate footprint of 8.9 ha (22 acres) in four expansion steps. Total depth is planned for 16 m (54 ft) providing 30 to 40 years of disposal capacity. Waste receipt averages approximately 49 TPD (120 tpd).

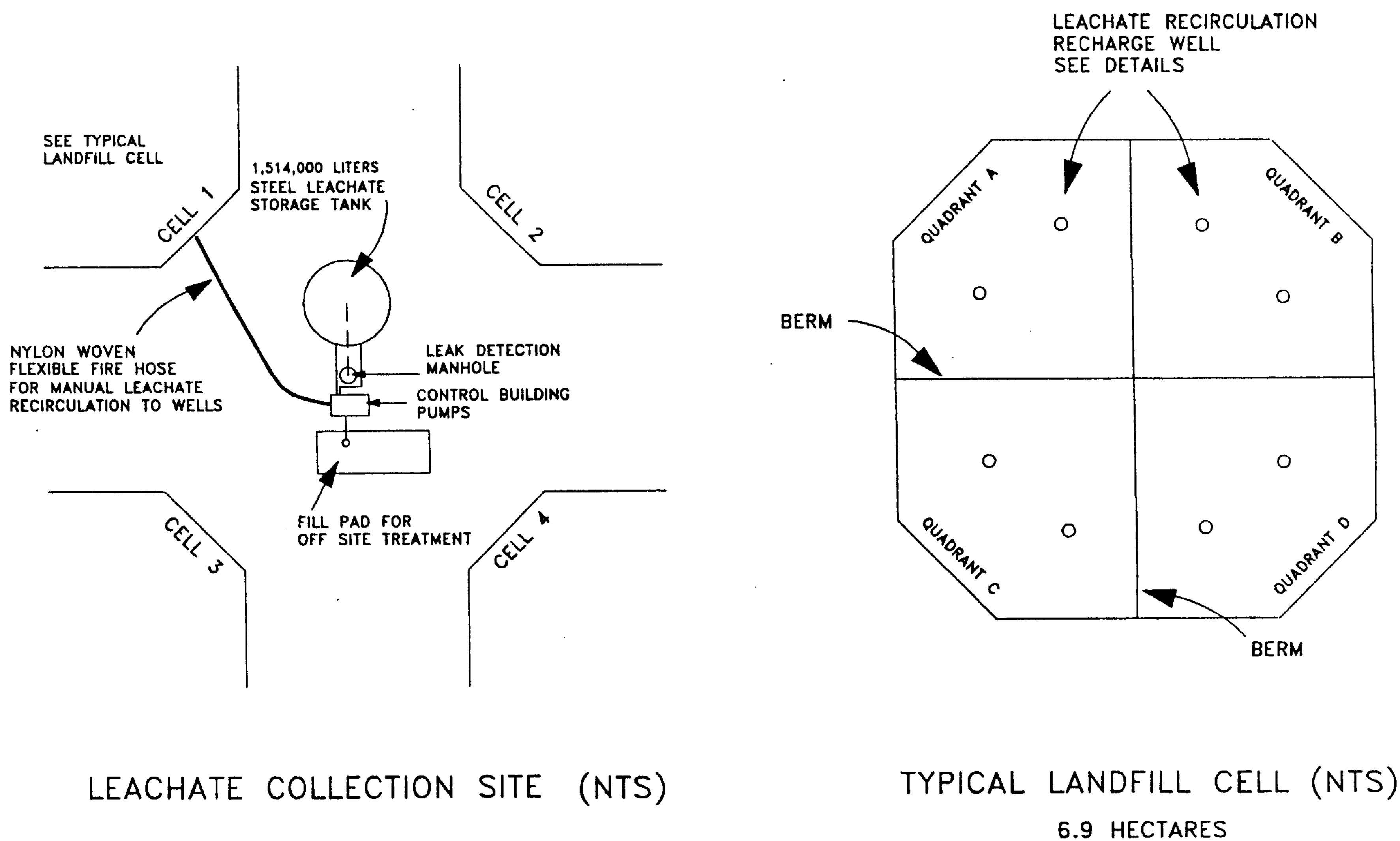


Figure 5-3. Leachate recirculation system, Worcester County, Maryland Landfill.

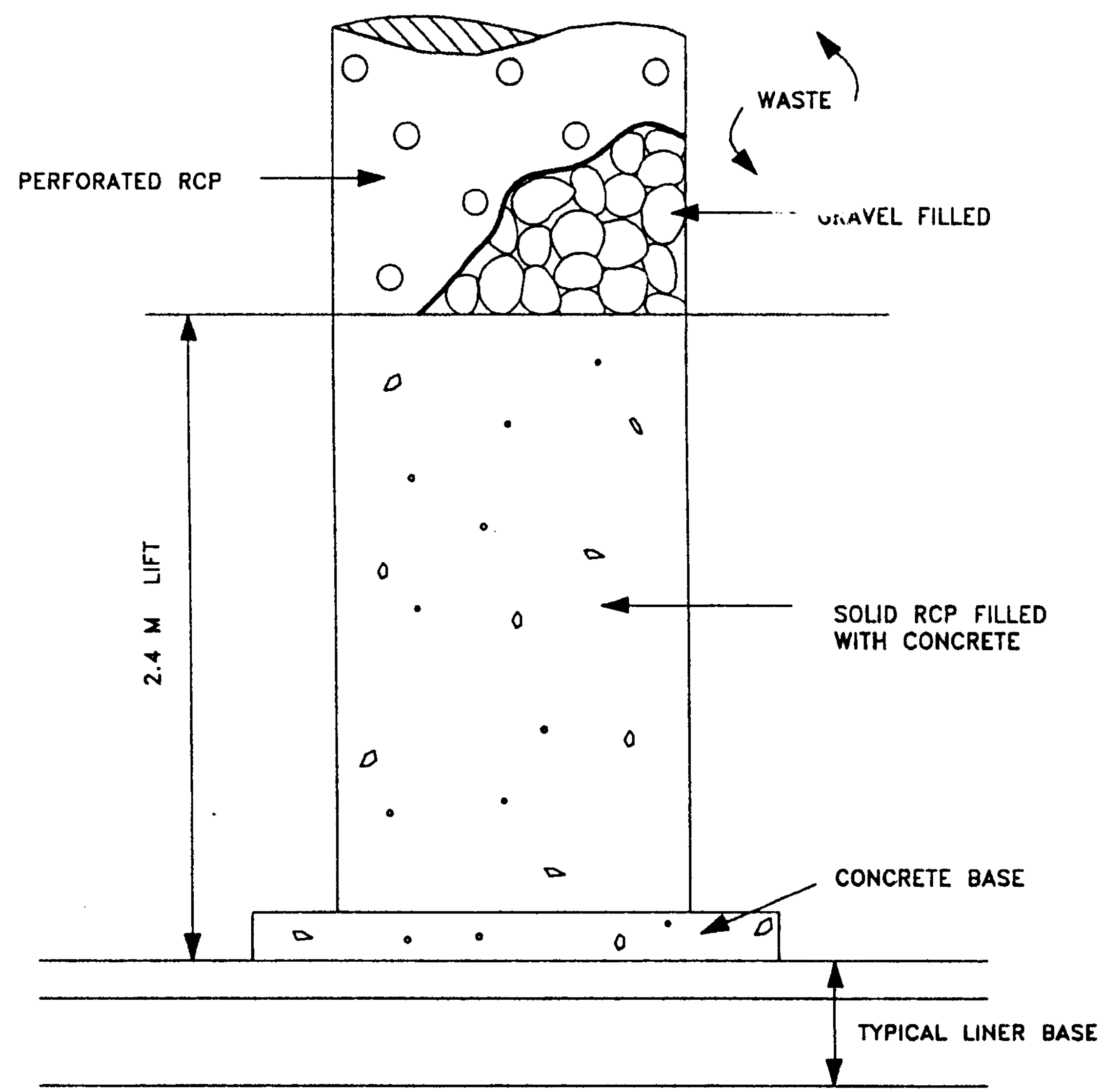


Figure 5-4 Vertical leachate recharge well, Worcester County, Maryland Landfill.

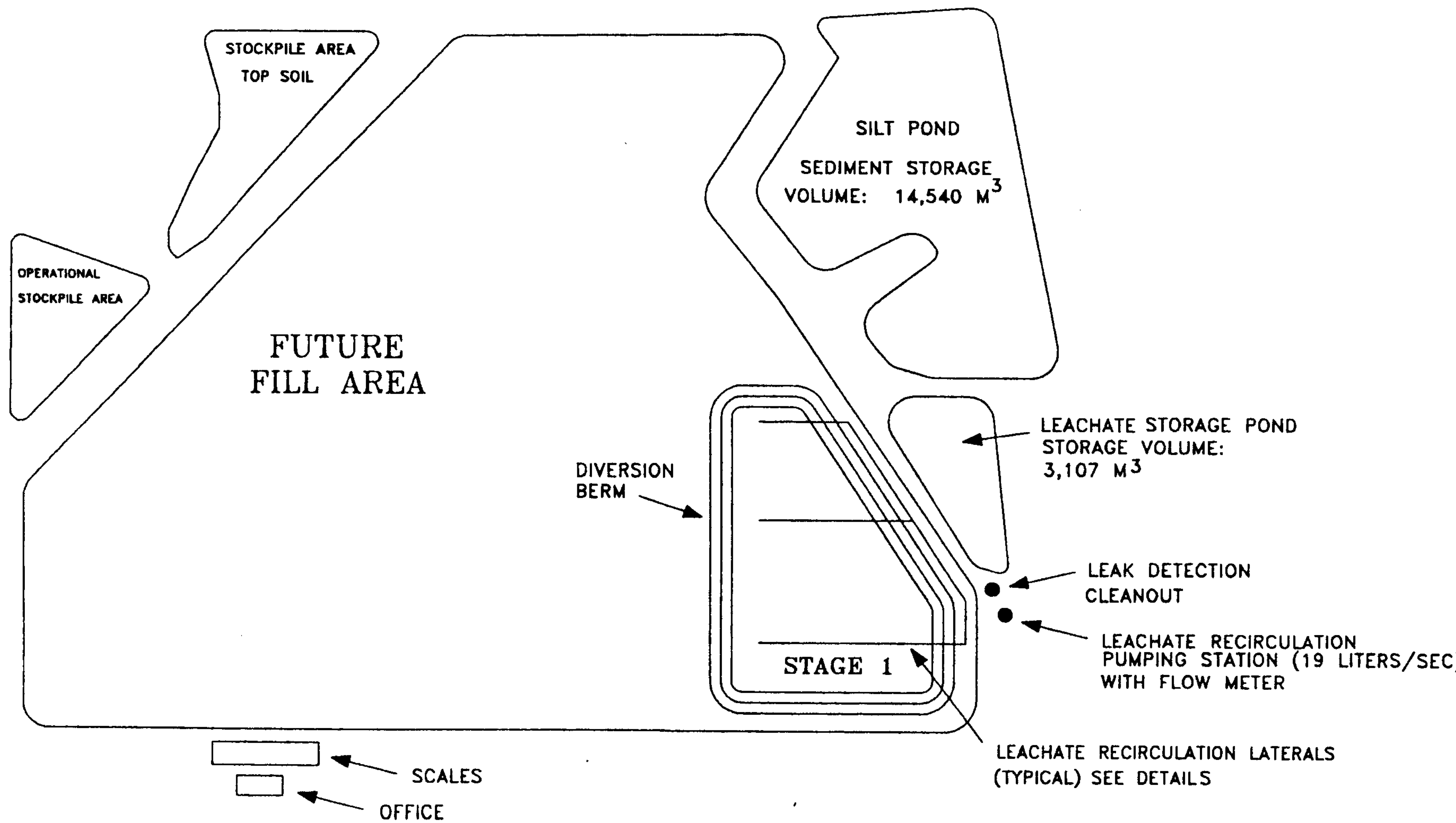


Figure 5-5 Pecan Row Landfill (Valdosta, GA).

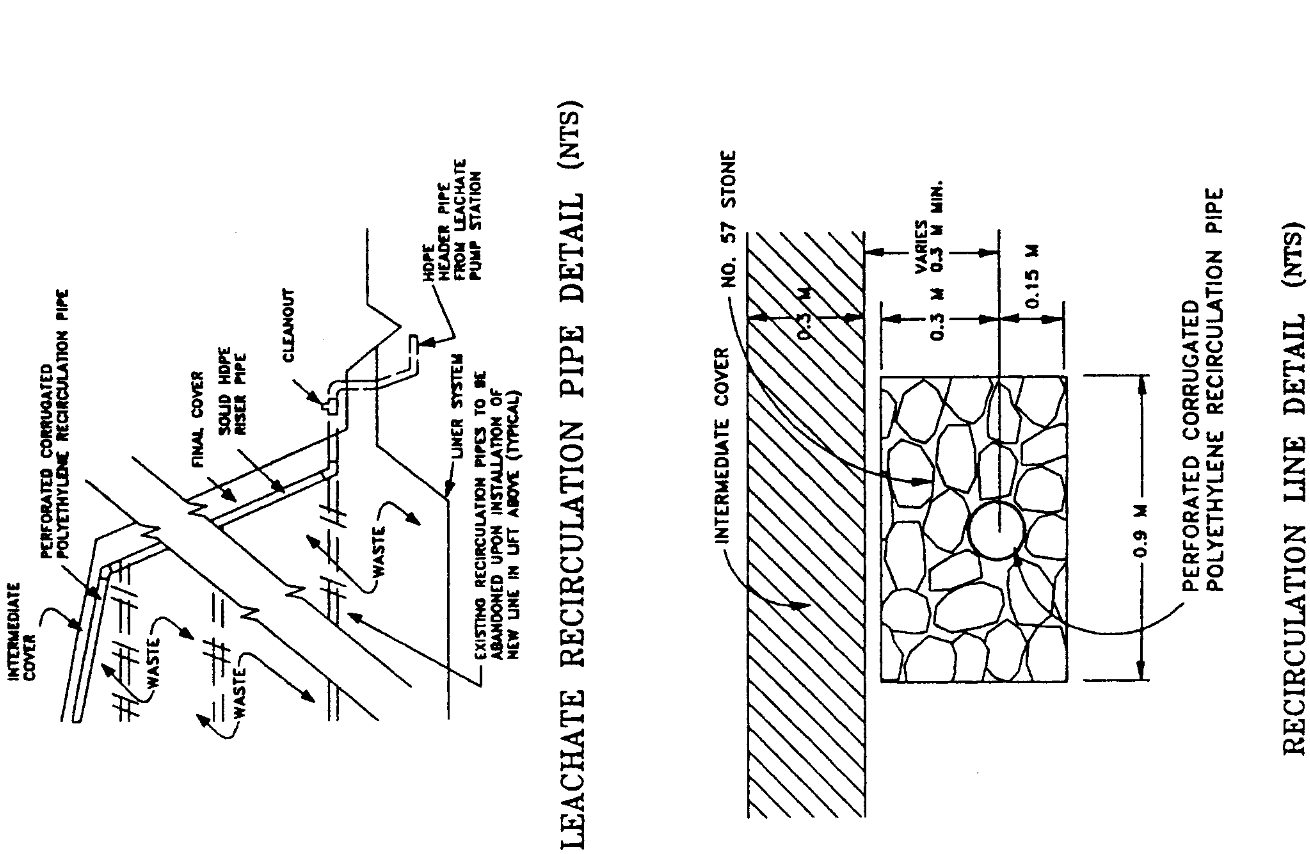


Figure 5-6. Pecan Row Landfill (Valdosta, GA) recirculation line detail.

It was observed that once the waste has been thoroughly wetted, 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.

Lower Mount Washington Valley Secure Landfill, Conway, New Hampshire

The Lower Mount Washington Valley Secure Landfill, located in Conway, New Hampshire is composed of eight hydraulically separated double-lined landfill cells (0.3 to 0.4 ha (0.75 to 1.0 acres)). Cell construction was completed in late 1991, with operations commencing in January of 1992. Waste receipt averages between 9,100 and 13,600 metric tons/year (10,000 and 15,000 tons/year). Leachate is stored in a 38-m^3 (10,000-gal) leachate collection tank.

Leachate recirculation began in May of 1992 at the first of eight cells, four months after start up. The primary mode of leachate recirculation was manual prewetting of waste using a fire hose to improve compaction and efficiently wet the waste. 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 to 1.8 m (four to six ft) deep, 0.9 to 1.2 m (three to four ft) wide, and 2.4 to 4.6 m (eight to 15 ft) long. However, shortcircuiting resulted due to the proximity of the sand drainage layer and this practiced was discontinued. High leachate generation rates were experienced during the spring of 1993, which were attributed to saturation of the fill while recirculating during the previous fall and winter, followed by freezing and then the spring thaw. Consequently, leachate recirculation was temporarily discontinued in November of 1993. To date, leachate recirculation has not resulted in excessive head on the 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.

Coastal Regional Solid Waste Management Authority Landfill, Craven County, North Carolina

The Coastal Regional Solid Waste Management Authority Landfill serves three counties along the eastern coast of North Carolina. Waste receipt averages around 320 TPD (350 tpd). 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 (2 ft) of drainage sand, a fabric filter, and a 0.15-cm (60-mil) HDPE liner overlying 0.6 m (2 ft) of low permeability clay was 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 reusable 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 4.5-million liter (1.2-MG) lined lagoons (4.6 m (fifteen 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 500 ft of flexible hose feeding a movable vertical injection system. A steel manifold distributes leachate through twelve 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 (3/4-in) diameter probes were 1.5 m (five ft) in length with 0.32-cm (1/8-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 (three m (ten ft)) were fabricated to minimize breakout. The diameter was increased to 3.2 m (1.25 in) with 0.64-cm (1/4-in) diameter holes. Breakouts continue to occur occasionally. Leachate recirculation pump flow rates vary between 200 and 300 lpm (55 and 80 gpm) 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 two to eight 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.

Lemons Landfill, Stoddard County, Missouri

The Lemons Landfill, owned and operated by the Lemons Landfill Corporation, is located on a 66-ha (162-acre) site in Stoddard County, Missouri. Fill area at build-out will be 30 ha (75 acres). Maximum depth will be 26 m (85 ft). Waste is received at a rate of approximately 270 TPD (300 tpd). 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 3,280 m^3 (867,800 gal). Figure 5-7 provides a schematic of the leachate management system.

Leachate recirculation will be accomplished using vertical wells located at 61-m (200-ft) spacing within the fill area (see Figure 5-8). Recirculation will be delayed until the area is filled and temporarily capped with 0.6 m (two ft) of clay. Recirculation is expected to commence approximately one year following initial waste receipt. The leachate recirculation well is constructed from a 1.2-m (48-in) diameter precast perforated concrete pipe filled with five to ten-cm (two to four-in) diameter stone. Within the structure are 30-cm (12-in) bentonite caps separating the well into three sections. PVC pipes (10-cm (four-in) diameter) are inserted into the wells reaching each of the three sections. The well structure rests on a 1.8-m (six-ft) square concrete pedestal underlain with a three-m (ten-ft) square, handtamped clay pad. Leachate distribution is supplemented by recharge laterals (7.5-cm (3-in) diameter PVC slotted pipe placed in 30-cm by 46-cm (12-in by 18-in) trenches) radiating out from each well at two depths.

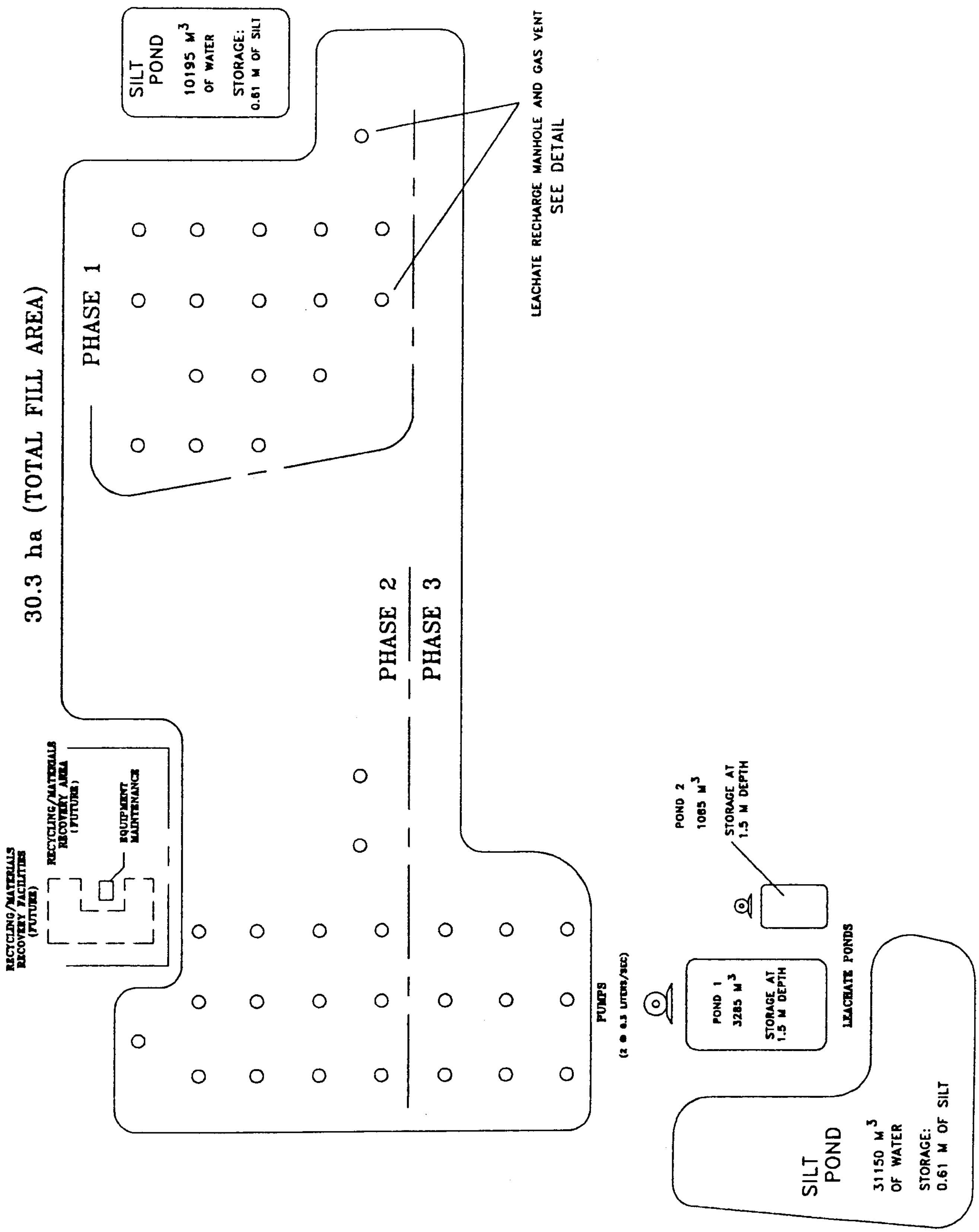


Figure 5-7. Lemon Landfill (Dexter, MO).

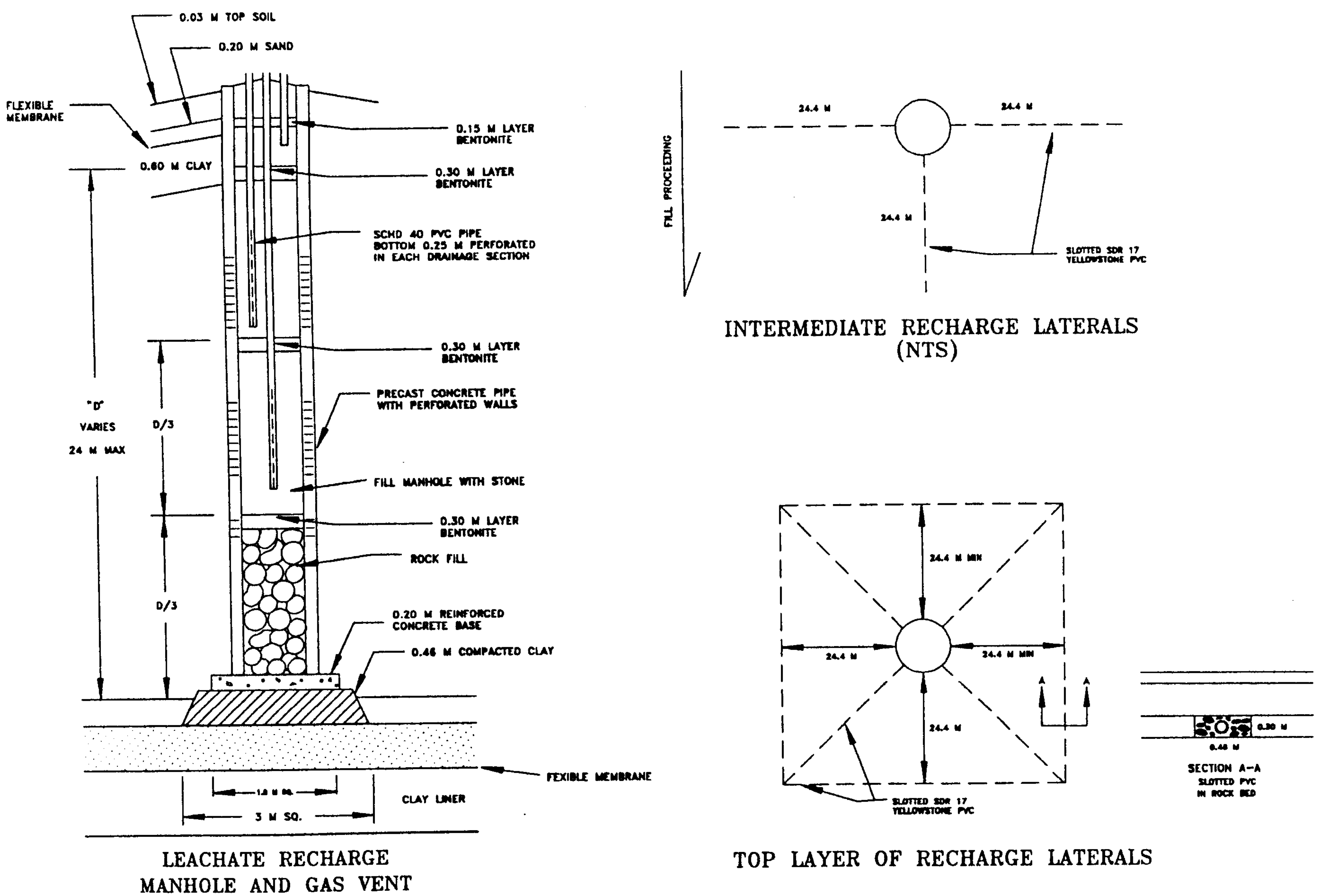


Figure 5-8. Lemon Landfill (Dexter, MO) leachate recirculation details.

Once leachate recirculation commences it will be collected in the first of two available storage ponds. Recirculation will continue until leachate strength is significantly reduced. 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 (two ft) of clay, 0.075-cm (30-mil) PVC geomembrane, and 0.3 m (one ft) of topsoil and seeded).

Mill Seat Landfill, Monroe County, New York

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 (three 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) foot print and a total waste depth of up to 34 m (110 ft).

Leachate recirculation is accomplished using two different horizontal introduction systems The systems are shown schematically at multiple elevations in Figures 5-9 through 5-11. The first system, installed in Test Cell 2, uses three pressurized loops constructed from ten-cm (four-in) diameter perforated HDPE pipe laid in trenches filled with crushed cullet, tire chips, or other permeable material. The loops have been provided at three elevations within the cell. Collected leachate will be directed to tanks providing a total of 110 m^3 (30,000 gal) 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 three-m (10-ft) deep horizontal trenches filled with permeable wastes and installed at two elevations. Prefabricated 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 (see Figure 5-12). 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 gal) storage. Prewetting of waste on occasion using water distribution trucks will also be practiced.

Recirculation rates are expected to be between 20 and 110 m^3/d (5,000 and 30,000 gpd). The relative moisture content of the waste will be monitored using gypsum blocks located in situ at depths of 11, 20, and 30 m (35, 65, and 95 ft) above the landfill liner. However, due to premature wetting of the blocks during waste filling, this system has not yielded any data. 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.

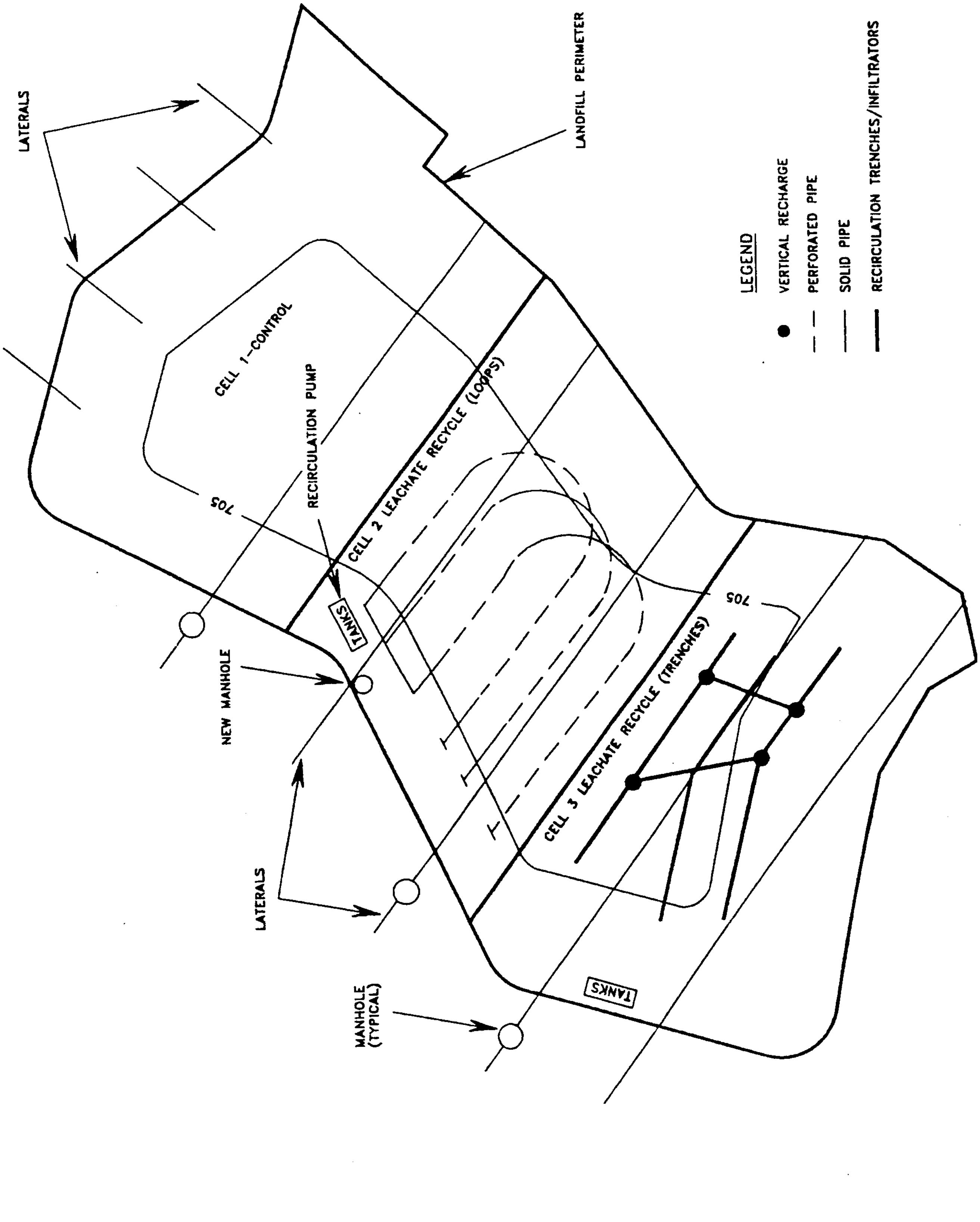


Figure 5-9. Mills Seat Landfill (Rochester, NY) recirculation layout (elevation 215 m).

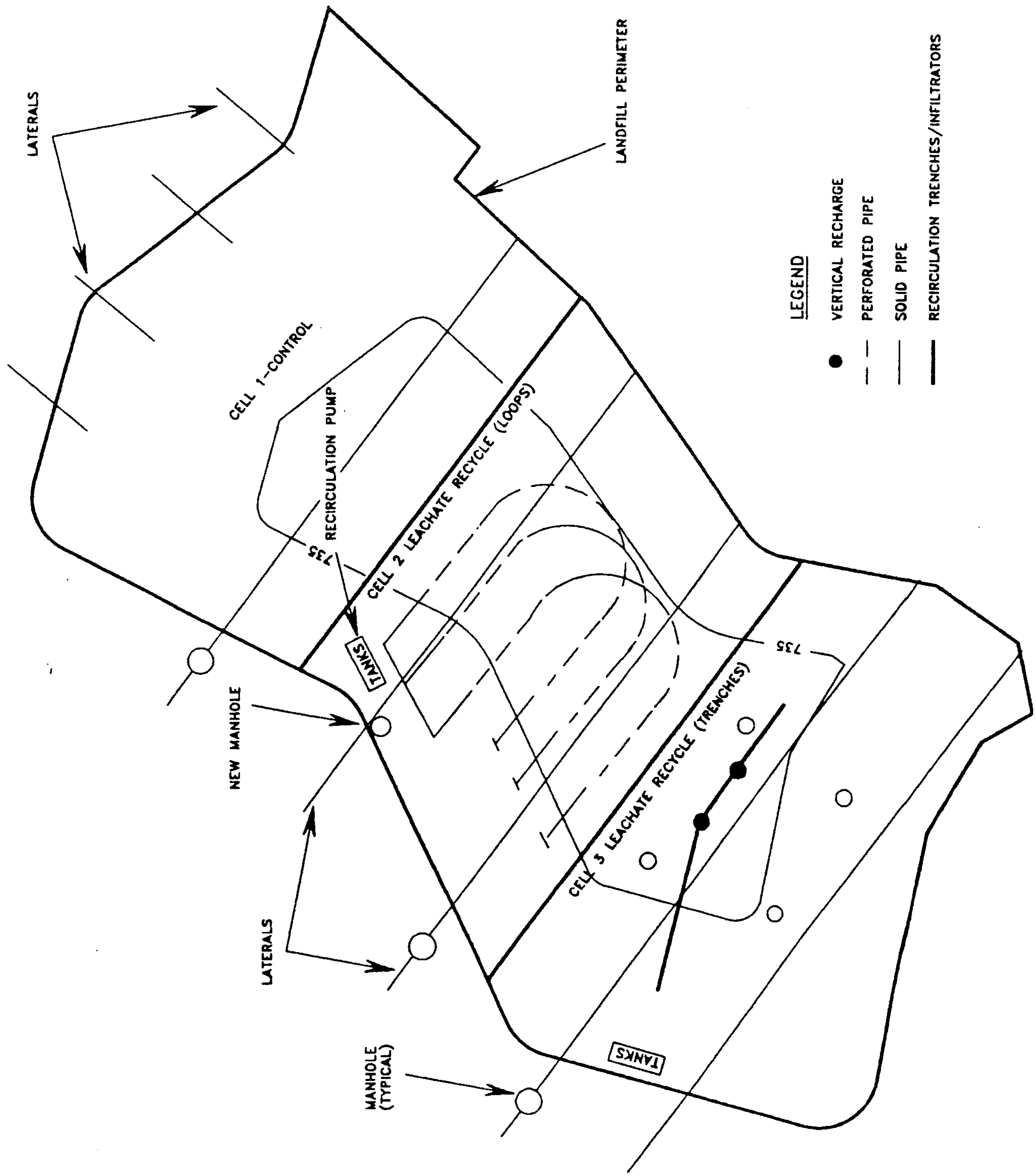


Figure 5-10. Mills Seat Landfill (Rochester, NY) recirculation layout (elevation 224 m).

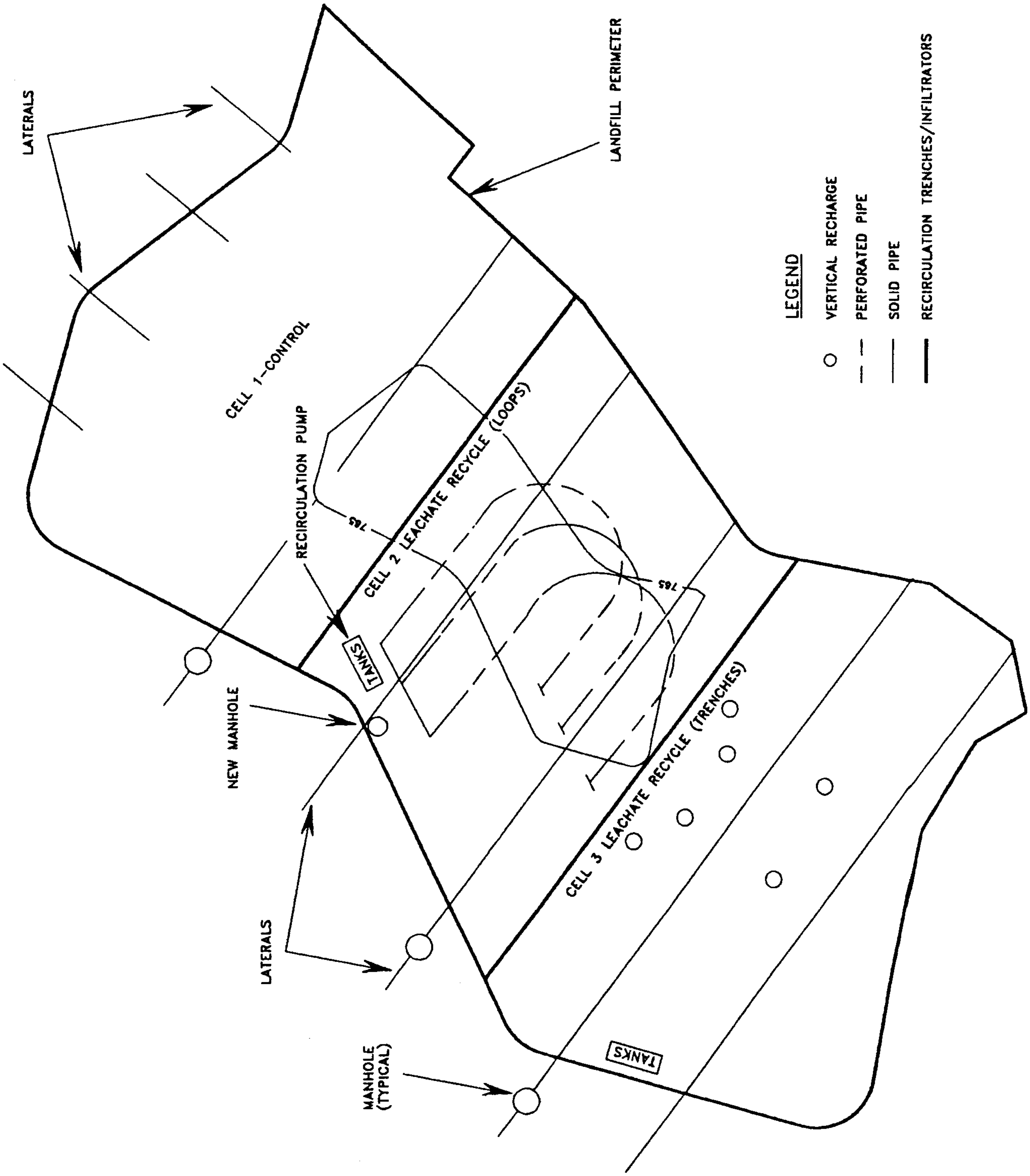


Figure 5-11. Mills Seat Landfill (Rochester, NY) recirculation layout (elevation 233 m).

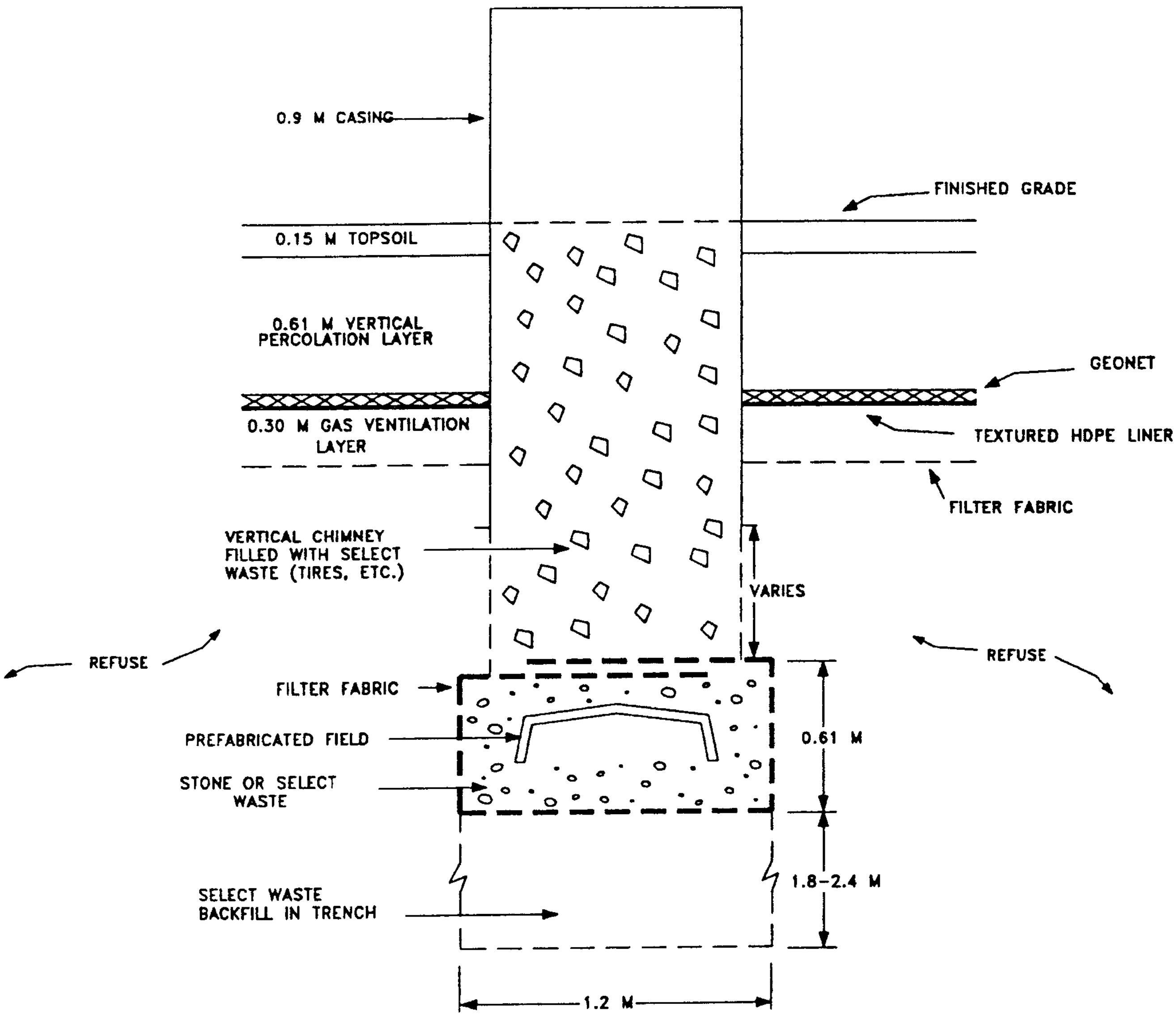


Figure 5-11. Mills Seat Landfill (Rochester, NY) prefabricated horizontal infiltration field with chimney

Yolo County Landfill, California

A demonstration initiative in Yolo County, California, funded by local and state governments was designed and constructed in 1993. Two, hydraulically separated 30 m by 30 m (100 ft by 100 ft) cells have been constructed to investigate impacts of leachate recirculation (see Figure 5-13). Leachate is introduced through a leach field at the top of one of the 12-m (40-ft) deep cells. The second cell will serve as a control. The control cell has a single composite liner, while the recirculation cell was constructed with a double composite liner. The bottom composite layer consists of 0.6 m (2 ft) of compacted clay, a 0.15-cm (60-milk) geomembrane, a drainage net, and geotextile. The top liner is composed of 30 cm (one ft) of compacted clay, a 0.15-cm (60-mil) geomembrane, drainage net, and geotextile. Independent leachate collection and removal systems have been provided.

Leachate is pumped to a distribution manifold located at the top of the test cell. (See Figure 5-14.) From the manifold, leachate is introduced at 25 locations across the surface through leachate injection pipes imbedded in a 1.5-m (five-ft) deep tire chip-filled injection pit. Warming of recirculated leachate and pH buffering are being considered as additional enhancement efforts. Within the fill, pressure transducers to monitor hydraulic head, temperature probes, and survey monuments to monitor settlement have been provided.

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 by 15-m (50 by 50-ft) area and was valved so that recirculation could be rotated from one area to another. An estimated 530 m^3/d (140,000 gpd) were recirculated to an area of 20 to 34 ha (50 to 60 acres) averaging 24 m^3/ha/d (2500 gal/acre/d). No clogging of the crushed stone was observed after operating for 5 years.

Recirculation is also practiced 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 reapplying leachate. One system pumps leachate from the two aerated lagoons (total storage 4,400 m^3 (1,150,000 gal)) and spray irrigates areas of the landfill which have been temporarily covered and seeded to maximize evapotranspiration opportunity during summer months. Year round, leachate is 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 programs are currently taking place in Sweden including a two-step degradation study conducted at Lulea, and an integrated landfill gas project involving landfills in

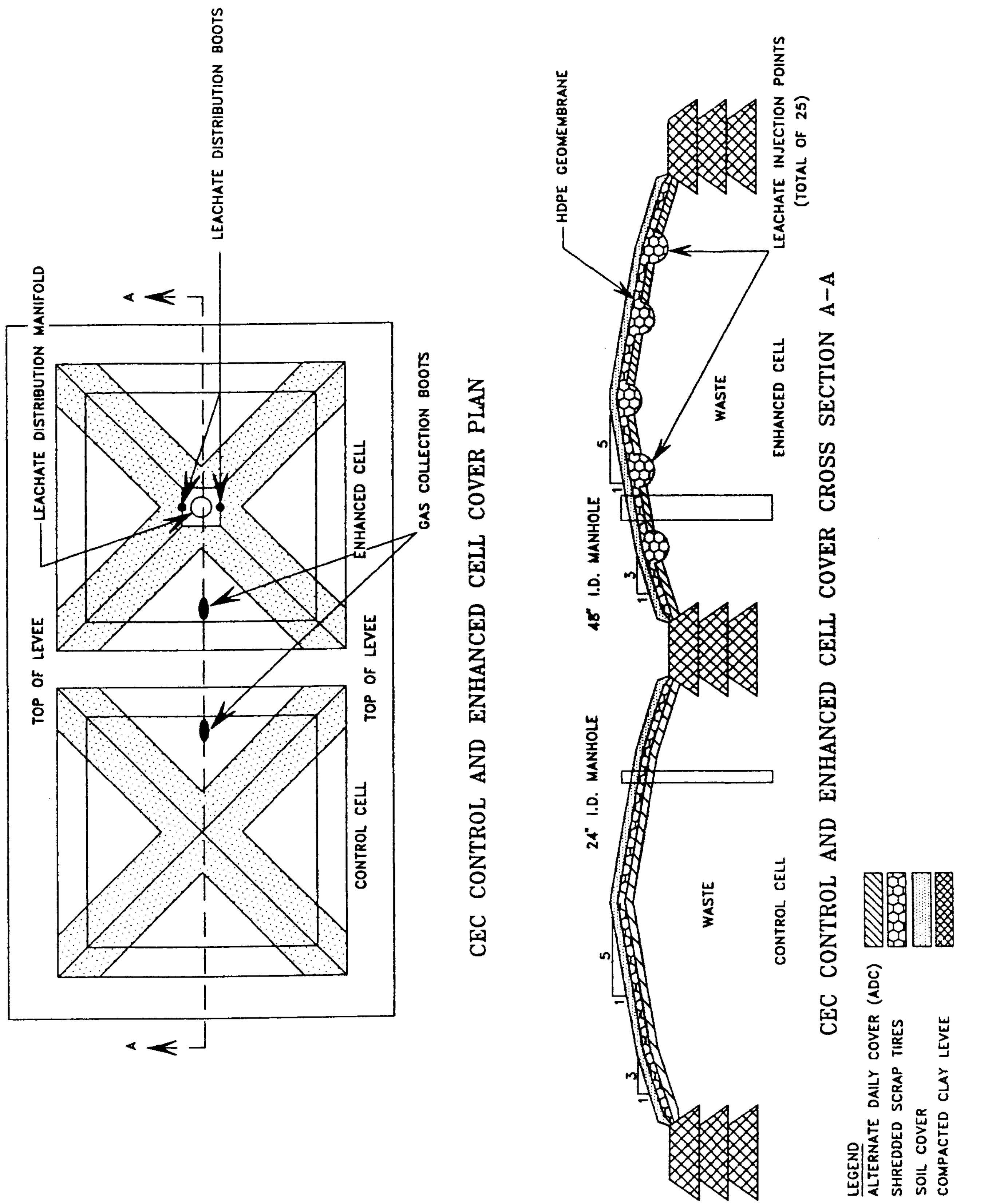


Figure 5-13. Yolo County Landfill (CA) test cells.

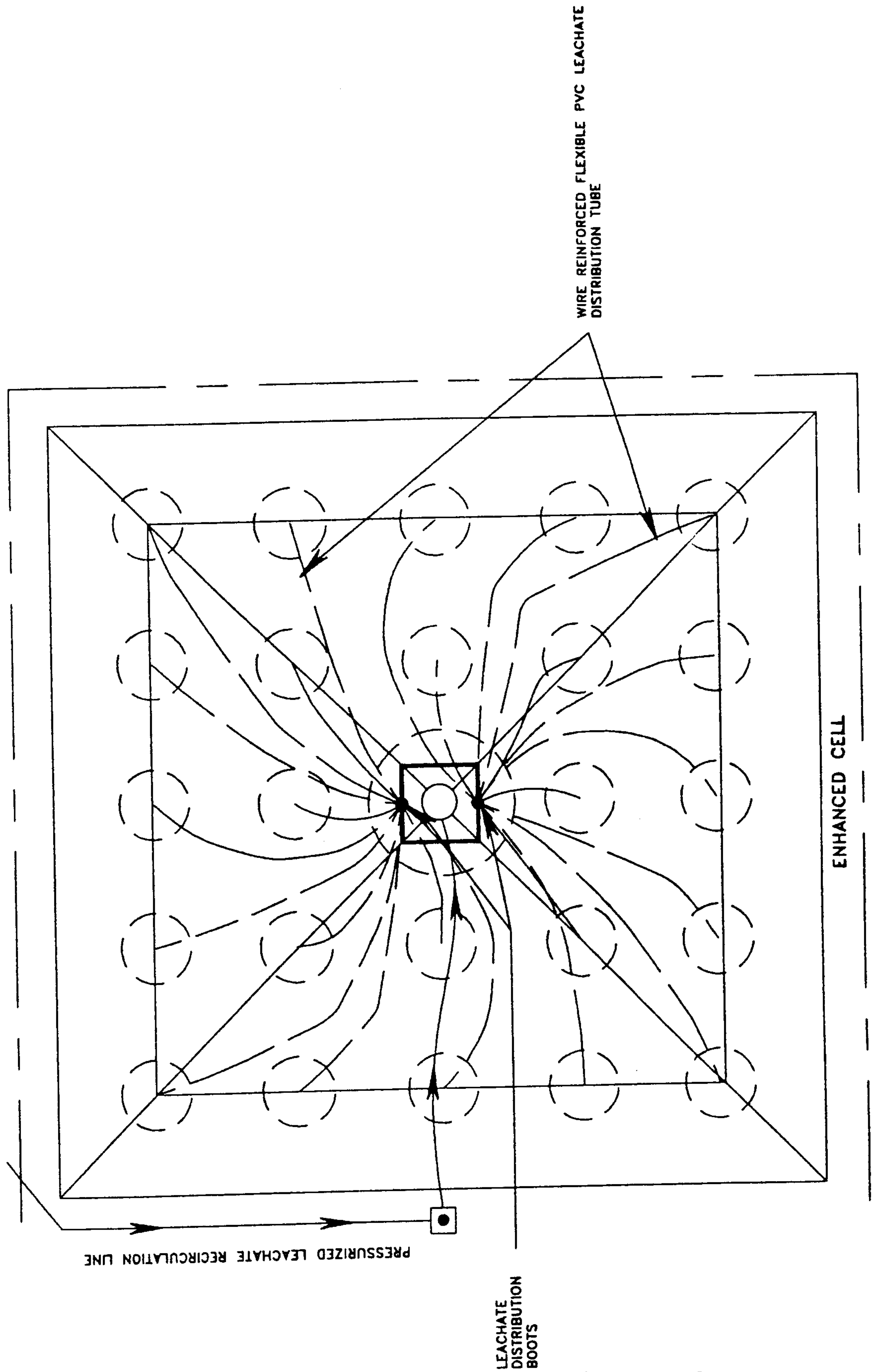


Figure 5-14. Yolo County Landfill (CA) leachate distribution system layout.

Helsingborg, Stockholm and Malmo, (Lagerkvist, 1991a, Lagerkvist, 1991b)

Two cells containing 450 m^3 (16,00 ft^3) of waste each were recently constructed in Viborg, Denmark to evaluate biogas production potential and enhancement methods. One cell contains only household waste, the second household waste and yard waste with leachate recirculation provided in both (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 and 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 1980's and leachate recirculation is planned at the Greenmount Landfill, the largest landfill in New Zealand. In San Pedro Sula, Honduras, a 250 TPD (275 tpd) landfill has been constructed to recirculate leachate using a low technology methodology (Gonzales, 1994). Leachate will be introduced to 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.

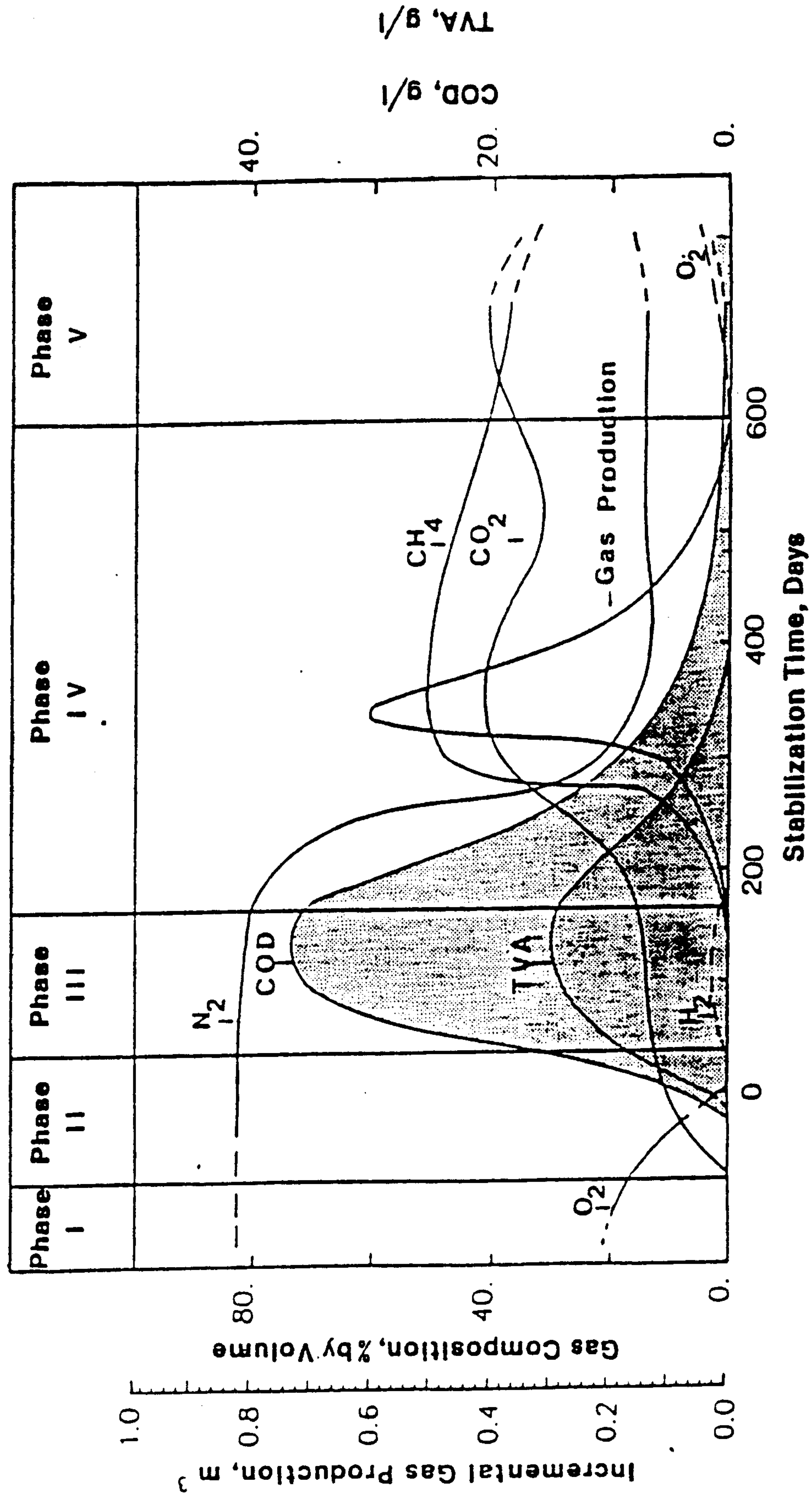


Figure 6-1. Stabilization phases of waste degradation in a landfill (reprinted by permission from F. G. Pohland).

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

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

Phase V - Maturation Phase
During the final state of landfill stabilization nutrients and available substrate become limiting, and the biological activity shifts to relative dormancy. Gas production dramatically drops and leachate strength stays steady at much lower concentrations. Because gas productions has all but ceased, atmospheric gases may permeate back into the landfill, and oxidized species may slowly appear. The slow degradation of resistant organic fractions may continue with the production of humic-like substances.

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

Leachate Characteristics
The characterization of leachate provides important information necessary for the control of landfill functions and for the design and operation of leachate treatment facilities, facilitates risk analysis of leachate impact on the environment should liners leak, permits comparison of the impact of alternative landfill design or operating protocol on the environment, and reveals the interaction of leachate parameters. Critical parameters for monitoring and control are described in more detail in Chapter 8.

Material is removed from the waste mass via mechanisms which include leaching of inherently soluble material, leaching of soluble products of biological and chemical transformation, and washout of fines and colloids. The characteristics of the leachate are highly variable depending on the composition of the waste, rate of water infiltration, refuse moisture content, and landfill design, operation, and age. These variations are demonstrated in Table 6-1, where ranges in

Table 6-1. Landfill Constituent Concentration Ranges as a Function of the Degree of Landfill Stabilization

Parameter	Phase II Transition		Phase III Acid Formation		Phase IV Methane Formation		Phase V Final Maturation	
	Conventional*	Recirculating#	Conventional*	Recirculating#	Conventional*	Recirculating#	Conventional*	Recirculating#
BOD, mg/l	100-10,000	0-6893	1000-57,000	0-28,000	600-3400	100-10,000	4-120	100
COD, mg/l	480-18,000	20-20,000	1500-71,000	11,600-34,550	580-9760	1800-17,000	31-900	770-1000
TVA, mg/l as Acetic Acid	100-3000	200-2700	3000-18,800	1-30,730	250-4000	0-3900	0	--
BOD/COD	0.23-0.87	0.1-0.98	0.4-0.8	0.45-0.95	0.17-0.64	0.05-0.8	0.02-0.13	1.05-0.08
Ammonia, mg/l-N	120-125	76-125	2-1030	0-1800	6-430	32-1850	6-430	420-580
pH	6.7	5.4-8.1	4.7-7.7	5.7-7.4	6.3-8.8	5.9-8.6	7.1-8.8	7.4-8.3
Conductivity, µmhos/cm	2450-3310	2200-8000	1600-17,100	10,000-18,000	2900-7700	4200-16,000	1400-4500	--

*Pohland and Harper, 1986

#Natale and Anderson, 1985; Watson, 1993; Miller, et al, 1994; Lechner, et al, 1993 concentrations of significant leachate components are presented as a function of stabilization phase.

Organic contaminants of leachate are primarily soluble refuse components or decomposition products of biodegradable fractions of waste. Organic compounds detected in 19 MSW landfill leachates or contaminated groundwater plumes emanating from landfills included organic acids, ketones, aromatic compounds, chlorinated aromatic compounds, ethers, phthalates, halogenated aliphatic compounds, alcohols, amino-aromatic compounds, nitro-aromatic compounds, phenols, heterocyclic compounds, pesticides, sulfur substituted aromatic compounds, polyaromatic hydrocarbons, polychlorinated biphenyls, and organophosphates (Brown and Donnelly, 1988).

The class of organic compounds found at highest concentration in leachates is generally VOAs produced during the decomposition of lipids, proteins, and carbohydrates (Albaiges, et al, 1986; Schultz and Kjeldsen, 1988). Aromatic hydrocarbons, including benzene, various xylenes, and toluene, are also frequently found at lower concentrations (Schultz and Kjeldsen, 1988; Harmsen, 1983). These compounds were considered to be constituents of gasoline and fuel oils. Sawney and Kozloski (1984) reported that the presence of the more soluble, less volatile aromatic components of gasoline in the leachate suggested that the more volatile components were being gas stripped from the landfill. Nonvolatile classes of compounds such as phenolic compounds may be degradative byproducts of lignin. A small complex fraction found in several leachates contained nicotine, caffeine, and phthalate plasticizers (Albaiges, et al, 1986). Oman and Hynning (1993) observed that a total of 150 different organic compounds have been identified in multiple studies, however only 29 were identified in more than one, concluding that leachate composition was quite site specific.

The dominant organic class in leachate shifts as the age of the landfill increases due to the ongoing microbial and physical/chemical processes within the landfill. An investigation of leachates obtained from landfills operated from one to twenty years found that the relative abundance of high molecular weight humic-like substances decreases with age, while intermediate-sized fulvic materials showed significantly smaller decreases (Chian, 1977). The relative abundance of organic compounds present in these leachates was observed to decrease with time in the following order: free VOAs, low molecular weight aldehydes and amino acids, carbohydrates, peptides, humic acids, phenolic compounds, and fulvic acids.

A variety of heavy metals are frequently found in landfill leachates including zinc, copper, cadmium, lead, nickel, chromium, and mercury (Lu, et al, 1985). Again, these metals are either soluble components of the refuse or are products of physical processes such as corrosion and complexation. In several instances heavy metal concentrations in leachate exceed US Toxicity Characteristic Leaching Procedures standards.

Heavy metal concentrations in leachate do not appear to follow patterns of organic indicators such as COD, BOD, nutrients, or major ions (Lu, et al, 1985). Heavy metal release is a function of characteristics of the leachate such as pH, flow rate, and the concentration of complexing agents.

Gas Characteristics

When solid waste decomposes, significant portions of organic wastes are ultimately converted to gaseous end-products. The rate of gas production is a function of refuse composition, climate, moisture content, particle size and compaction, nutrient availability, and buffering capacity. Reported production rates vary from 0.12 to 0.41 m^3/kg (3800 to 13,000 ft^3/ton) dry waste (Pohland and Harper, 1986). Production rates and gas composition also follow typical stabilization phases (see Figure 6-1), with peak flow rates and methane content occurring during the methanogenic phase. Landfill gas is typically 40 to 60 percent methane, with carbon dioxide and trace gases such as hydrogen sulfide, water vapor, hydrogen, and various volatile organic compounds comprising the balance.

Because of their high vapor pressures and low solubilities, many toxic volatile organic compounds (VOCs) are observed in landfill gas. In a report by the State of California Air Resources Board (Bennett, 1987), the average surface emission rate of hazardous chemicals from landfills was estimated to be 35 kg/million kg of refuse. Landfill gas trace constituents include halogenated aliphatics, aromatics, heterocyclic compounds, ketones, aliphatics, terpenes, and alcohols and have been characterized by several researchers (Siu, et al, 1989; Young and Parker, 1983; Wood and Porter, 1987; LaRegina and Bozzeli, 1986).

Leachate Characteristics of Recirculating Landfills

Leachate quality data were collected from five full-scale recirculating landfills located in Lycoming County, PA; the Central Solid Waste Management Center (CSWMA), Sandtown, Delaware; the Southwest Landfill, Alachua County, FL; the Central Facility Landfill, Worcester County, MD, and the Breitnau Research Landfill, Austria, previously described in Chapters 4 and 5. Results of preliminary analysis of the data are summarized in Tables 6-1 and 6-2. Table 6-1 provides leachate characteristics as a function of landfill stabilization phase for both conventional and recirculating landfills, while Table 6-2 compares all data. Due to differences in waste age and heterogeneity of conditions found within each landfill, explicit transitions between stabilization phases cannot be determined exactly. Nevertheless, boundaries between such phases were delineated based on the approximate magnitudes of leachate and gas strength (*i.e.* COD and BOD concentrations, and methane production) obtained from the records at these sites. Furthermore, a comprehensive understanding of stabilization sequence and features as illustrated in the literature, provided the necessary guidance in dividing the stabilization histograms into their consecutive stages, and projecting the overall values of leachate and gas parameters.

From these data it appears that leachate characteristics of recirculating landfills follow a pattern similar to that of conventional landfills, *i.e.*, moving through phases of acidogenesis, methanogensis, and maturation (although few recirculating landfills have reached maturation). These data (as summarized in Table 6-2) do not suggest that contaminants extensively concentrate in the leachate as has been promoted by critics of leachate recirculation (King and Mureebe, 1992). Actually, the overall magnitude of various leachate components, during the consecutive phases of landfill stabilization, are quite comparable in both types of landfills. However, the acidogenic phase tends to be more pronounced in recirculating landfills as opposed to conventional landfills, forming a plateau with consistently high concentration of leachate constituents (Al-Yousfi, 1992). Such a phenomenon can be explained by the fact that uniform, high moisture contact opportunities exist in the leachate recycling landfills. On the other hand, dryness in areas of conventional landfills, accompanied by fewer chances of moisture contact and availability, minimizes the leaching opportunity in such landfills, and result in rapidly peaking leachate histograms.

Table 6-2. Leachate Constituents of Conventional and Recirculating Landfills - Summarizing all Phases

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

*Pohland and Harper, 1986
#Natale and Anderson, 1985; Watson, 1993; Miller, et al, 1994; Lechner, et al, 1993

Even in the case where recycled leachates are somewhat stronger than single-pass leachates, they are primarily treated inside the landfill, utilizing its storage and degradation capacity as an effective bioreactor. No extra liability and/or handling requirements will result from such cases, because leachate is repeatedly recirculated back into the landfill until its strength diminishes and stabilizes. In this respect, frequency of recirculation can be employed as a control measure to optimize landfill operations and alter leachate characteristics as desired.

Fate and Transport of Priority Pollutants

The fate of inorganic and organic compounds placed in a landfill is determined by the operative processes inherent to the natural stabilization phases occurring within the landfill. Contaminants tend to partition among aqueous, solid, and gaseous phases of the landfill. Contaminant mobility and fate is largely determined by the magnitude of the preference for one phase relative to another which is a function of the physical/chemical characteristics of both the contaminant and the phases present.

Figure 6-2 depicts the transport/transformation phenomena which may affect the environmental fate of a landfilled contaminant. Mechanisms of mobility and transformation include biotransformation, volatilization, dissolution and advection, sorption, and chemical reactions such as precipitation, reduction, oxidation, and hydrolysis. Biotransformation and chemical reaction can reduce contaminant mass, however, a more toxic and/or mobile compound may be produced. Dissolution and advection results in the movement of the compound with the bulk flow through the refuse pore spaces. Similarly, volatilization and transport by the product gas can remove the

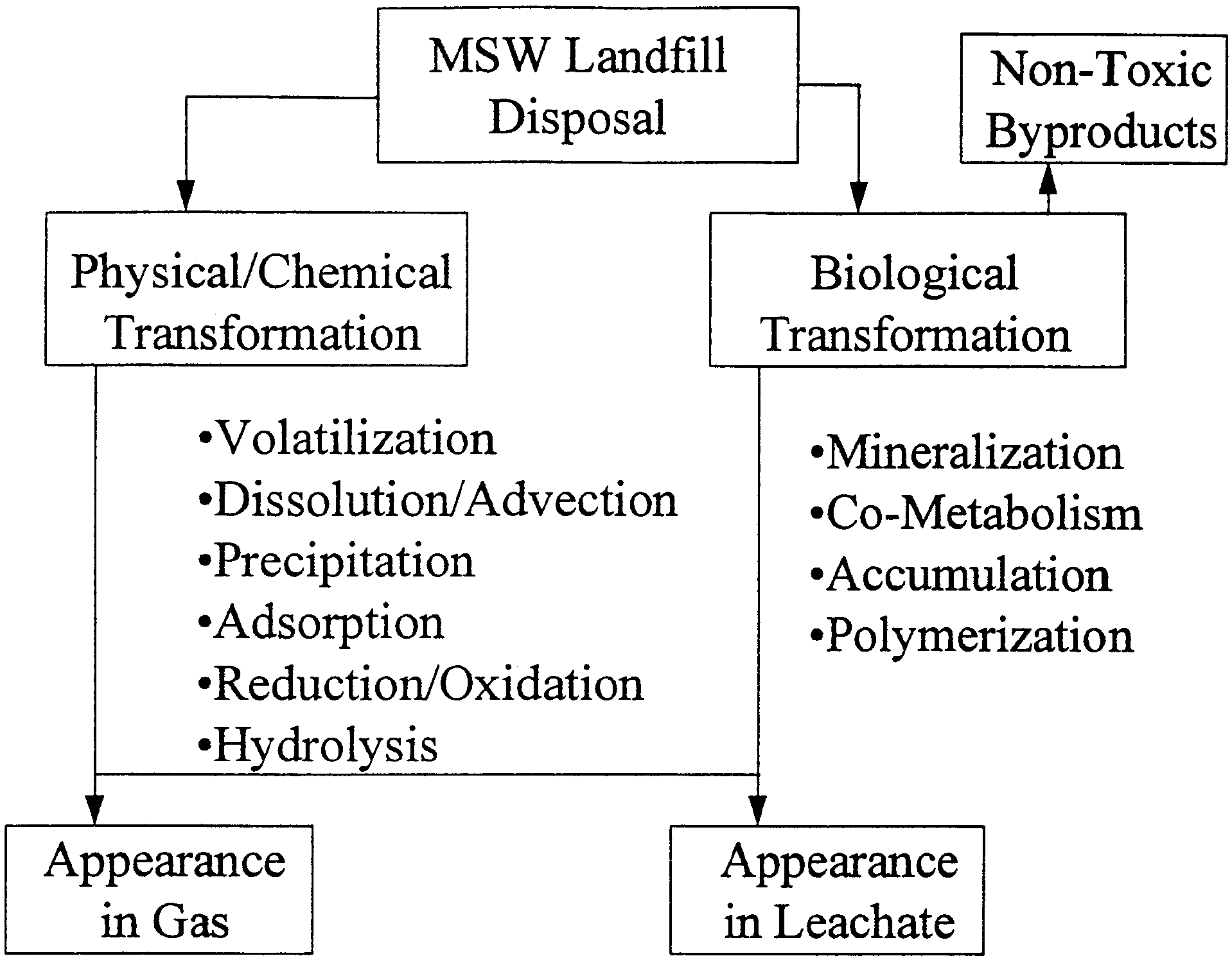


Figure 6-2. Fate and transport mechanisms for contaminants in MSW landfills.

more volatile contaminants from the landfill. Sorption and precipitation can retard contaminant movement as the compound interacts with the solid phase. Transport can be influenced by compound complexation or chelation which can either retard movement if the complex becomes associated with the solid phase or enhance mobility if the compound "piggybacks" on a more soluble complexing agent.

The fate of twelve organic priority pollutants codisposed with municipal solid waste in lysimeters was investigated by researchers at the Georgia Institute of Technology (Pohland, et al, 1992). The lysimeters were constructed in pairs of recirculating and single-pass operation and are described in more detail in Chapter 4. The organic priority pollutants were attenuated by abiotic and biotic transformation as well as partitioning to the waste mass. Reductive dehalogenation was the principal mechanism for halogenated compounds. Evidence suggested the possible reduction and mineralization of some aromatic compounds. The conversion of organic pollutants was enhanced in the recirculating columns due to reduced oxidation-reduction potential and stimulated methanogenesis.

Relatively few metal contaminants were routinely measured in laboratory-scale landfill bioreactor studies other than iron and magnesium, however antimony, arsenic, beryllium, cadmium, chromium, copper, iron, lead, magnesium, and zinc are monitored at pilot and full-scale sites, presumably to meet regulatory requirements. With the exception of iron, magnesium, and arsenic (at the Delaware test cells), metal concentrations were reportedly below detection limits.

In the presence of leachate recirculation, iron concentrations tended to decline with time, while remaining constant in conventionally operated landfills. Where leachate-recirculating sites were continuing to receive waste, however, iron concentrations remained elevated.

The primary removal mechanism for metals in conventionally operated landfills appears to be washout, although limited chemical precipitation may occur. In leachate-recirculating landfills, the primary removal mechanism appears to be metal sulfide and hydroxide precipitation and subsequent capture within the waste matrix by encapsulation, sorption, ion-exchange, and filtration (Pohland, et al, 1992). Gould, et al, (1989) found that leachate recirculation stimulated reducing conditions in lysimeters, providing for the reduction of sulfate to sulfide, which moderated leachate metals to very low concentrations. Chian and DeWalle (1976) reported that the formation of metal sulfides under anaerobic conditions effectively eliminated the majority of heavy metals in leachate. In addition, under neutral or above neutral leachate conditions, promoted by leachate recirculation, metal hydroxide precipitation is enhanced. With time, moderate to high molecular weight humic-like substances are formed from waste organic matter in a process similar to soil humification. These substances tend to form strong complexes with heavy metals. In some instances, a remobilization of precipitated metals can result from such complexation once the organic content has been stabilized and oxic conditions begin to reestablish (Pohland, et al, 1992). The potential for remobilization supports the idea of inactivating the landfill (removing all moisture) once the waste is stabilized.

Comparison of Waste Stabilization Rates

The rate of waste placement can significantly impact leachate characteristics. Waste placed in a laboratory column will behave more or less as described above, following distinct phases of transition, acidogenesis, methanogenesis, and maturation. Once methanogenesis is established, the leachate organic strength generally declines. In order to quantify the impact of leachate recirculation of leachate stabilization, a comparison of the rate of decline in the COD for recirculating and single-pass operations was made. Because of the limited available operational information for these studies, a rigorous kinetic analysis of the sequential reactions was not possible. However, a non-linear regression of chronological, declining COD data was performed for a series of laboratory studies of leachate recirculation and conventional, single-pass operations described in Chapter 4 (Pohland, 1975; Pohland, et al, 1992; Tittlebaum, 1982, Pohland, 1985). From the rate of decline, COD half-lives can be calculated and compared. Half-lives are presented in Table 6-3, where it can be seen that, in most cases, recirculation accelerated leachate stabilization, as attested by the shorter half-life of COD within the recirculating lysimeters.

A similar analysis of leachate COD for full-scale leachate recirculating landfills having moved to maturation phases was made with results also provided in Table 6-3. Here, half-lives were nearly

Table 6-3. COD and Chloride Half-Lives in Laboratory, Pilot and Full-Scale Leachate Recirculation Studies, Years

Study	COD		Chloride	
	Recirculating	Single-Pass	Recirculating	Single-Pass
GIT (Pohland, 1975) (L)	0.21	0.69	0.73	0.29
GIT (Pohland, et al, 1985)(L)	0.19	--	1.2	--
Tittlebaum, 1982 (L)	0.07	3.75	0.43	0.47
GIT (Pohland, et al 1992) (L)	0.43	0.41	1.77	0.51
Austria (Lechner, et al 1993) (P)	0.64	--	--	--
DSWA (Watson, 1993) (P)	0.32	0.27	1.8†	4.21
DSWA (Watson, 1993) (F)	1.05	--	2.89	--
Lycoming, PA (Natale and Anderson 1985) (F)	0.78	--	2.58	--

L = laboratory-scale, P = pilot-scale, F = full-scale

†This value is a doubling time since chloride concentration is increasing

five times greater than those of laboratory recirculating lysimeters. As discussed previously, a full-scale landfill does not usually depict a single degradation phase, but rather overlapping phases representing various sections, ages, and activities within the landfill. In addition, full-scale leachate recirculating devices are generally less efficient than those used in the laboratory, therefore portions of the full-scale landfill may be relatively dry. Also, greater compaction in the field vs. the laboratory will negatively impact leachate routing. Thus full-scale landfills may experience slower decay rates than laboratory fills.

Unfortunately, the relative efficacy of leachate recirculation in enhancing waste degradation relative to conventionally operated landfills at full-scale is difficult to quantify, because of the lack of conventional/recirculation parallel operations. Recognizing this limitation, leachate COD data were gathered from the literature for conventional landfills. These data and their sources are provided in Appendix B and are plotted in Figure 6-3. The data were analyzed to determine a COD half-life as described above. A COD half-life of approximately 10 years was calculated for conventional landfills as compared with values of 230 to 380 days for recirculating landfills.

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

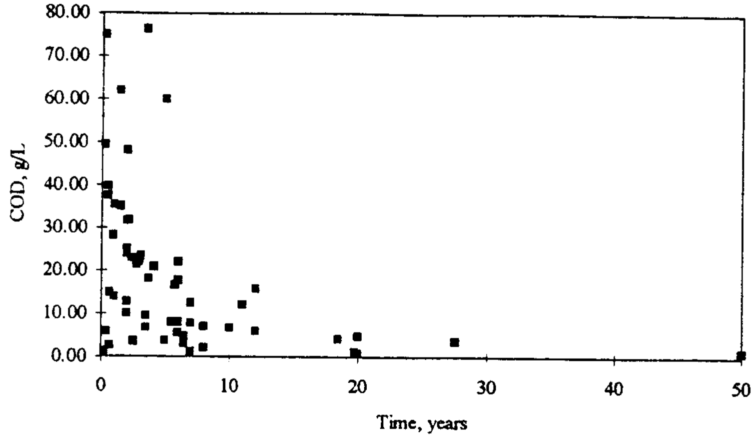


Figure 6-3. Leachate COD from conventional landfills.

COD is removed from single-pass landfills via washout and biological conversion and from recirculating landfills primarily by accelerated biological conversion. A conservative parameter such as chloride would be removed from single-pass landfills via washout, however in a recirculating landfill, chloride would only be removed when leachate was discharged to off-site treatment and disposal. Therefore, chloride would be expected to decline in concentration over time in a single-pass landfill, while staying relatively constant or more slowly declining in a recirculating fill (see Figure 6-4). This behavior has been observed at all scales. Chloride half-lives were calculated as described above for COD and are reported in Table 6-3 where this behavior is confirmed quantitatively (*i.e.* considerably higher chloride half-lives in recirculating fills than in conventional landfills). A comparison of COD and chloride half-lives should provide an independent means of confirming the impact of leachate recirculation on leachate components, assuming the leachate is evenly distributed and methanogenesis is occurring. The opposite effects of leachate recirculation on the conservative parameter chloride and the nonconservative parameter COD should provide a COD/chloride half-life ratio of well below one. For single-pass operations, the value should be greater than or equal to one. Limited data are available to test this hypothesis, however this trend is seen in Table 6-4.

Table 6-4. Ratios of COD/Chloride Half-Lives

Reference	Recirculating	Single-Pass
Pohland, 1975 (L)	0.29	2.38
Pohland, et al 1985 (L)	0.16	--
Tittlebaum, 1982 (L)	0.019	1.08
Pohland, et al, 1992 (L)	0.24	0.8
DSWA, 1993 (P)	0	--
Watson, 1993 (F)	0.36	--
Natale and Anderson, 1985 (F)	0.30	--

Leachate Treatment Implications

Ideally, the bioreactor landfill should be operated to minimize off-site management of leachate, however, eventually treatment of leachate will be necessary. Following extended recirculation, the leachate will be largely devoid of biodegradable organic matter, and will contain recalcitrant organics and inorganic compounds such as ammonia, chloride, iron, and manganese. Table 6-1 and 6-2 provide some indication of the quality of mature leachate from recirculating landfills. Treatment needs depend upon the final disposition of the leachate. Final disposal of leachate may be accomplished through codisposal at a publicly owned treatment works (POTW) or onsite treatment and direct discharge to a receiving body of water, deep well injection, land application, or via natural or mechanical evaporation.

Leachate treatment can be challenging because of low biodegradable organic strength, irregular production rates and composition, and low phosphorous content (if biological treatment is considered). Because of the nature of leachate, physical/chemical treatment processes such as ion exchange, reverse osmosis, chemical precipitation/filtration, and carbon adsorption are the most likely options. Available leachate treatment processes are discussed by several authors (Pohland and Harper, 1986; Lema, et al, 1988; Chian and DeWalle, 1976; Cossu and Urbini, 1989; Venkataramani, et al, 1986). Generally, where on-site treatment and discharge is selected, several unit processes are required to address the range of contaminants present. For example, a recently constructed leachate treatment facility at the Al Turi Landfill in Orange County, New York utilizes polymer coagulation, flocculation, and sedimentation followed by anaerobic biological treatment, two-stage aerobic biological treatment, and filtration prior to discharge to the Wallkill River (King and Mureebe, 1992). Pretreatment requirements may address only specific contaminants which may create problems at the POTW. For example, high lime treatment has been practiced at the Alachua County Southwest Landfill to ensure low heavy metal loading on the POTW.

Leachate Quantities

Leachate volumetric data from full-scale recirculating landfill sites described in Table 5-1 and plotted in Figure 6-5 show that greater volumes of leachate are produced as recirculation rates increase. Also, recirculated leachate represents an increasing percentage of generated flows (asymptotically approaching 100 percent) as recirculation rates increase. With the current landfill capping practices, recirculated leachate volumes will become especially dominant after landfill closure. Of the six operating sites analyzed, leachate generation rates ranged from 1.1 to 13.5 m^3/ha/day (300 to 2100 gal/acre/day), with recirculated leachate representing 40 to 70 percent of leachate generated. As with conventional landfills, leachate generation is a function of climate and site characteristics, as well as leachate recirculation rates.

Off-site disposal of leachate ranged from 0 to 59 percent of leachate generated. Data suggested that, unlike conventional landfills, the volume of leachate requiring off-site management at recirculating landfills was a function of both the volume of leachate generated and the available on-site storage. At sites where large storage volumes were provided relative to the size of the landfill cell, off-site management of leachate was minimized (frequently no off-site management

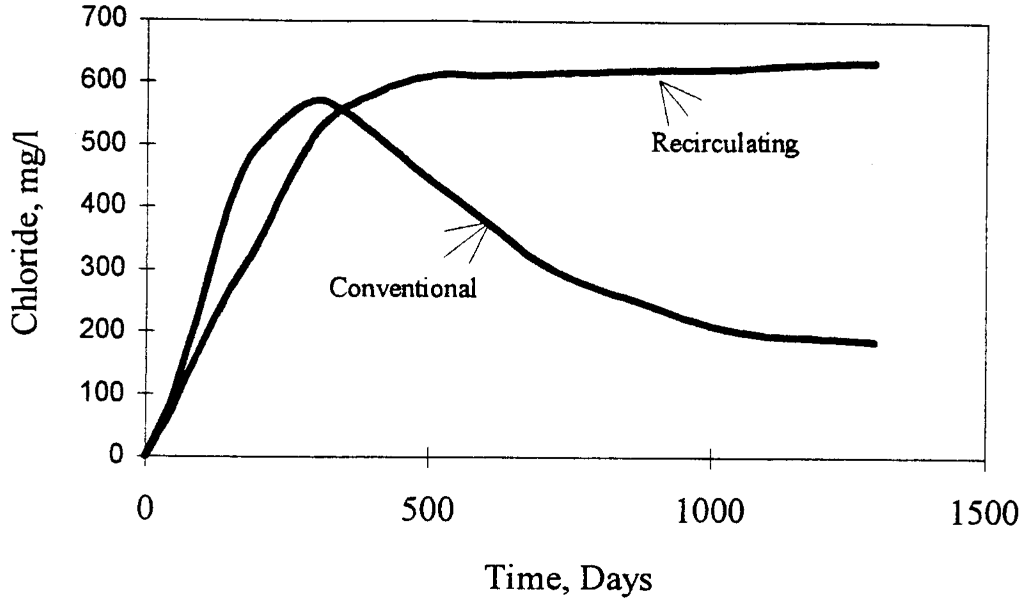


Figure 6-4. Typical Behavior of chloride in conventional and recirculating landfills.

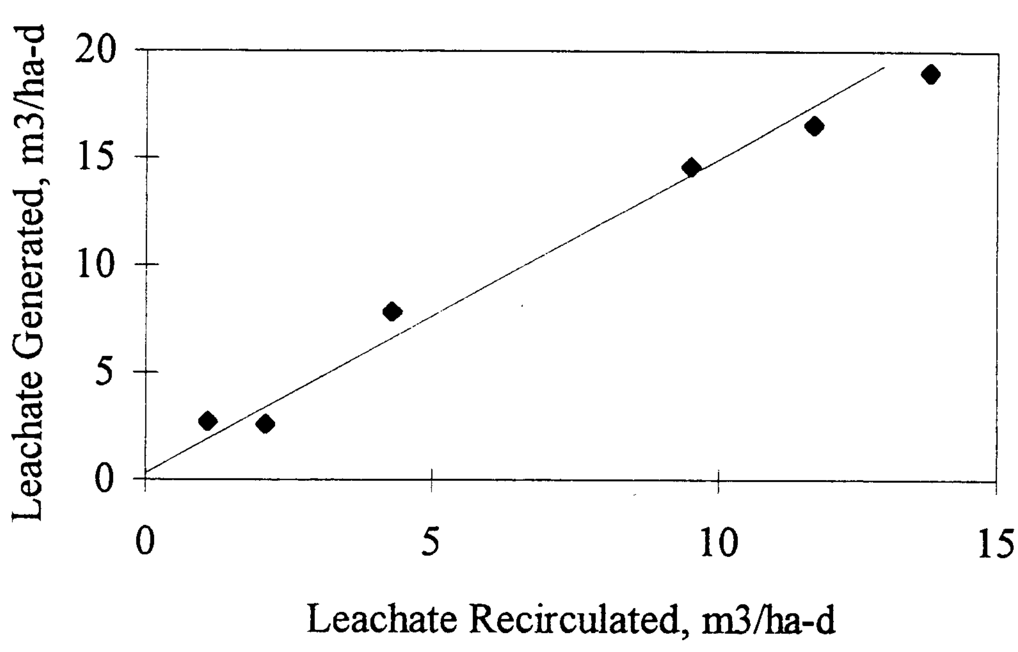


Figure 6-5. Effect of leachate recirculation on leachate generation.

was required for long periods of time). It was also observed that sites with relatively little storage were compelled to recirculate leachate at much higher rates than those with large storage volumes.

Gas Production

While gas production is relatively easy to determine from laboratory lysimeters, full-scale measurement of gas emissions from active sites is more difficult to achieve. Limited data suggest that, as in lysimeters, gas production is significantly enhanced as a result of both accelerated gas production rates 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). Parallel 2.5-ha (one-acre) cells operated by the Delaware Solid Waste Authority comparing conventional operation and leachate recirculation showed a twelve-fold increase of gas production in the recirculating cell relative to the conventional cell (5400 std m^3 vs 480 std m^3 (190,000 std ft^3 vs 17,000 std ft^3), DSWA, 1993).

Gas emission measurements were made by University of Central Florida (Orlando) researchers at a recirculating landfill in Alachua County, Florida using a patented device, the Flux Tube (a variation on the flux chamber used to measure surface emissions). These tests revealed a doubling of gas production rates from waste located in wet areas of the partially recirculating landfill relative to comparably aged waste in dry areas (0.0236 std m^3/kg-yr vs. 0.0096 std m^3/kg-yr (750 std ft^3/ton-yr vs 300 std ft^3/ton-yr, Palumbo, 1995). This fact was corroborated by measurements of biological methane potential (BMP) from samples obtained in wet and dry areas of the same landfill (Miller, et al, 1994). A 50 percent decrease in BMP was measured in wet samples (46 percent wet basis) over a one year period. Negligible decreases in BMP were observed in dry samples (29 percent wet basis) over the same period.

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.

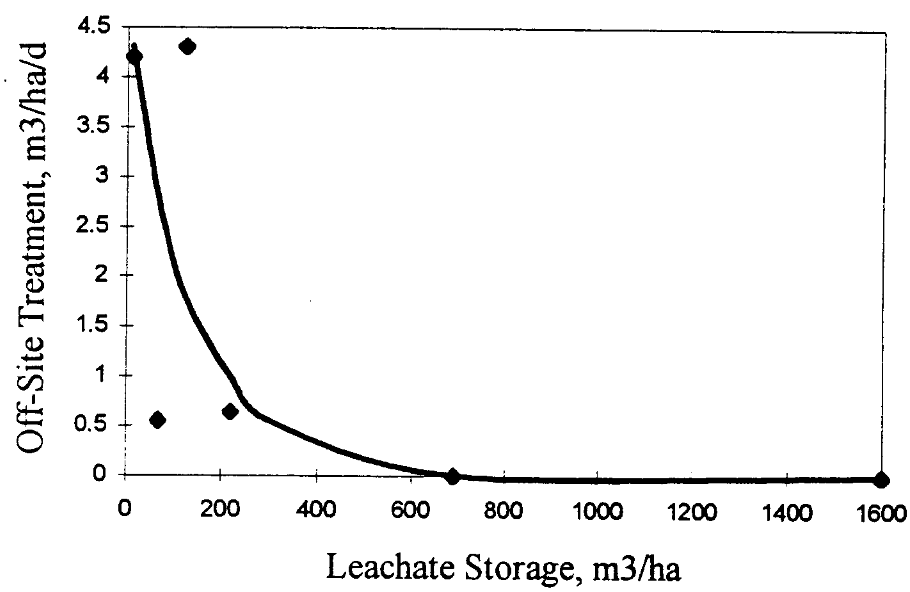


Figure 7-1. Effect of leachate storage on off-site treatment requirements.

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 (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	(A) Merritt, 1992 - noncontinuous injection rate industrial landfill, hydraulic conductivity 10^{-2} cm/sec (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

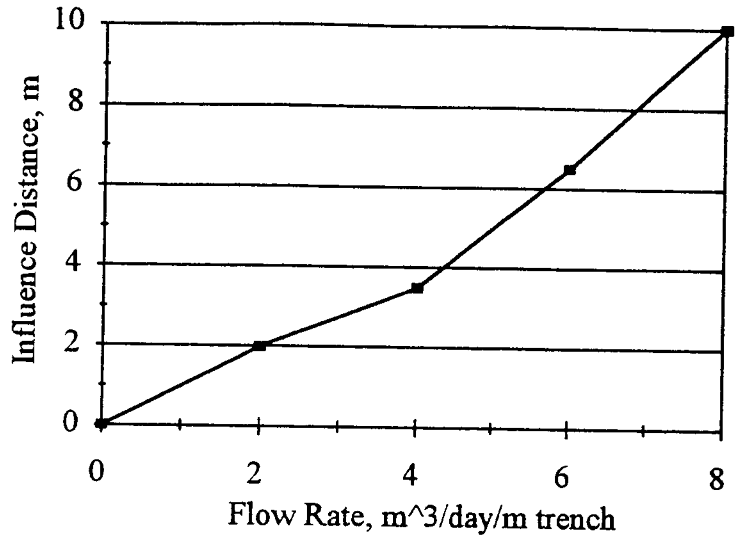


Figure 7-2. Influence distance of horizontal trench.

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 10cm/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 Apendix 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 degee 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.

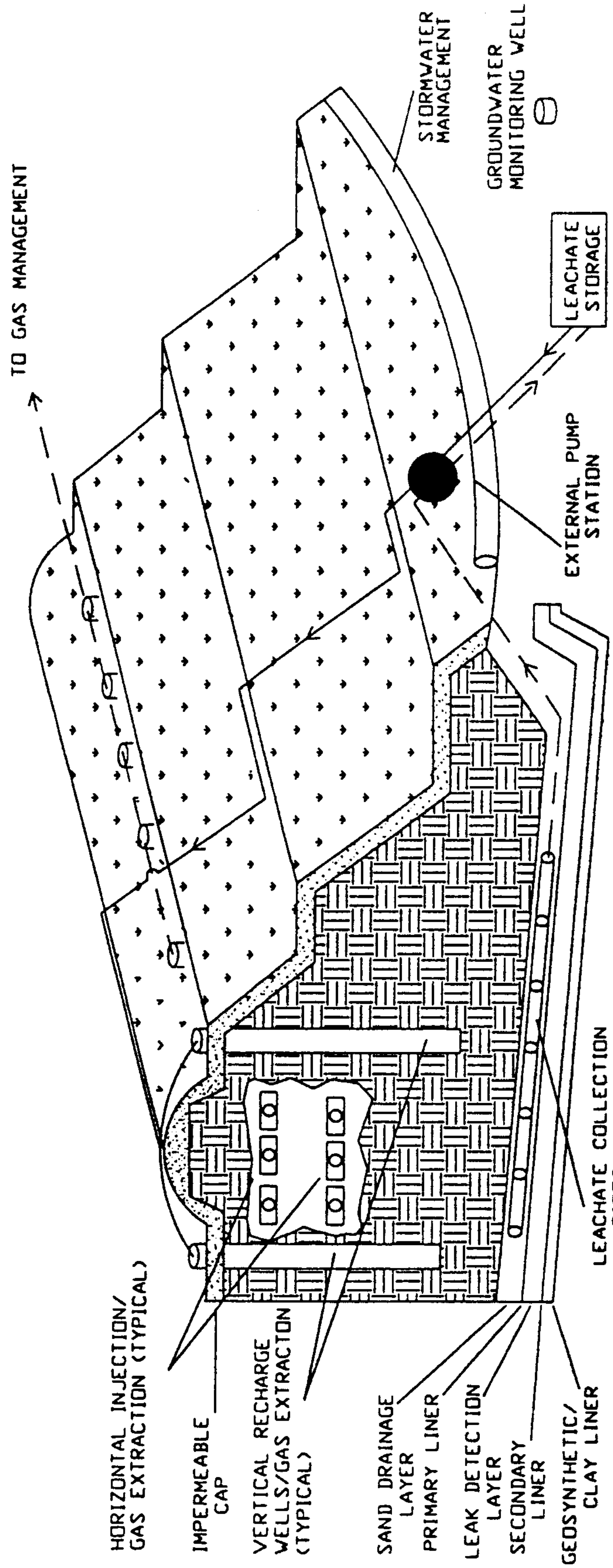


Figure 7-3. Schematic diagram of leachate recirculating landfill.

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

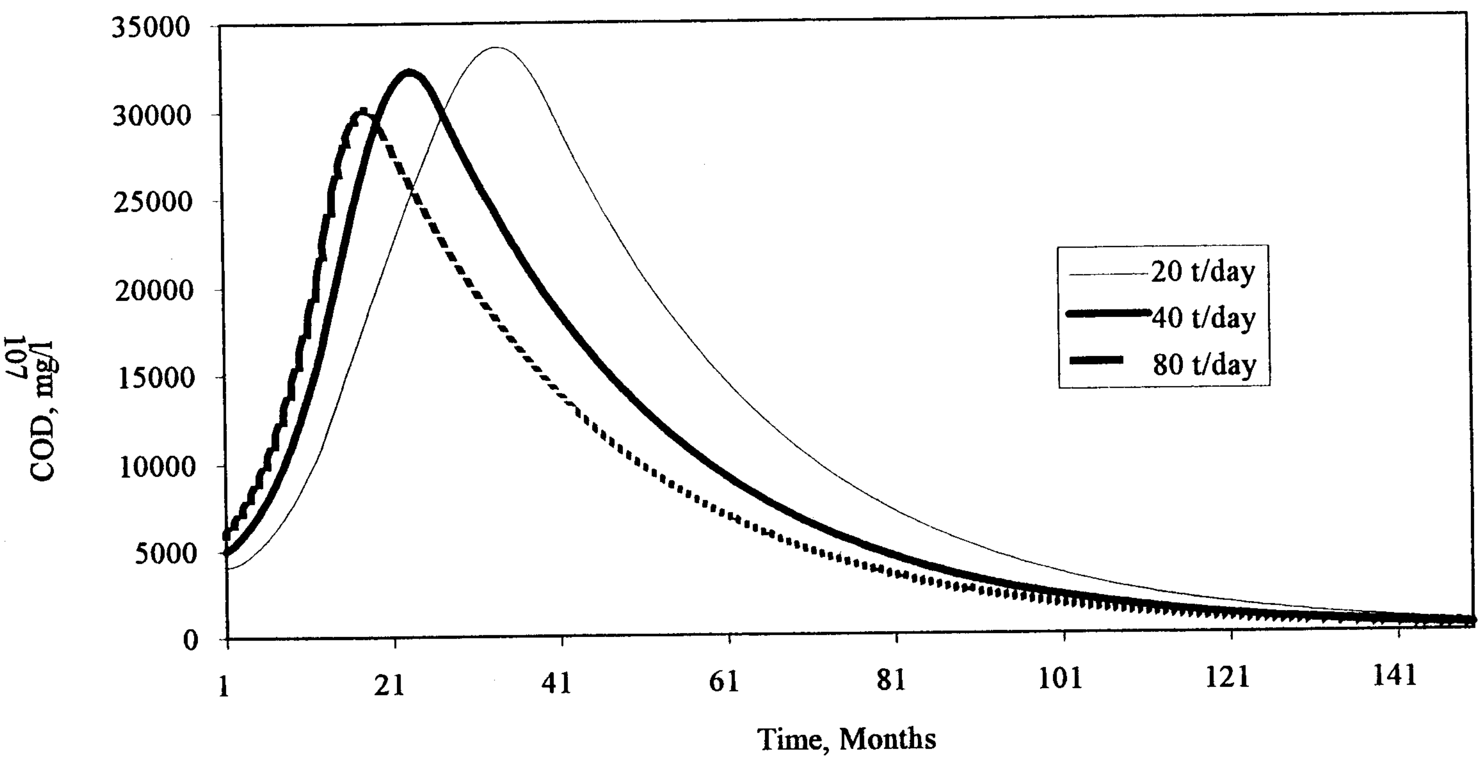


Figure 8-1. Effect of waste placement rate on leachate quality.

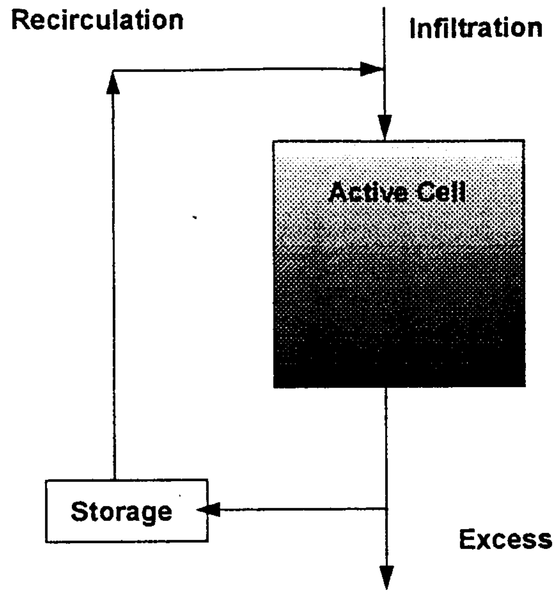


Figure 8-2. Leachate recirculation scenario - single cell.

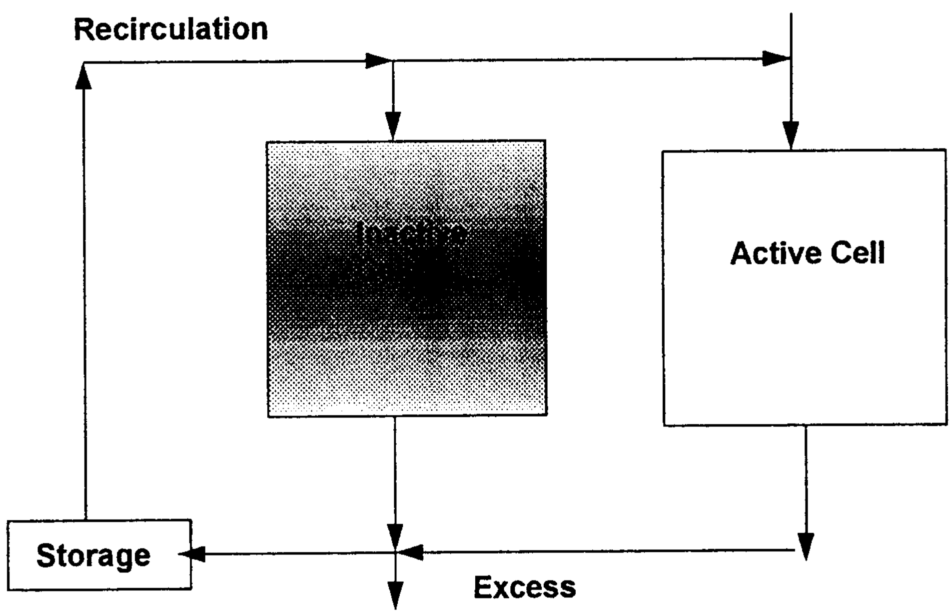


Figure 8-3. Leachate recirculation scenario- two cell sequencing.

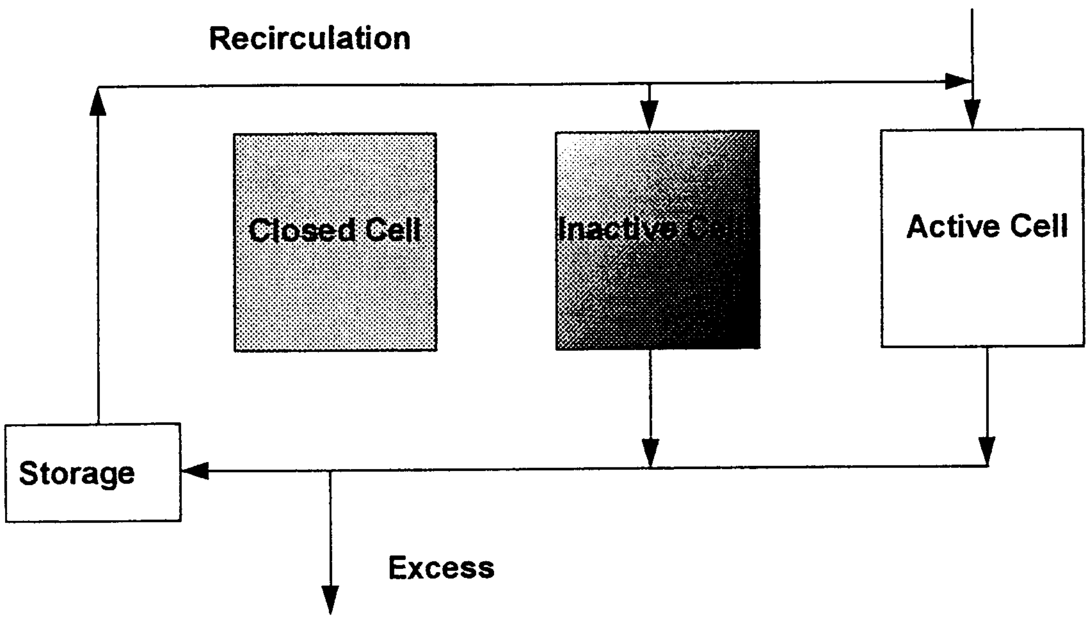


Figure 8-4. Leachate recirculation scenario - closed cell.

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 composi on,

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:				x	
Cellulose/lignin Ratio	Twice annually				
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.

References

Agora, Santosh. *Mathematical modeling of leachate recirculating landfills.* M.S. Thesis, University of Central Florida, Orlando, Florida, 1995.

Albaiges, J., F. Casado, and F. Ventura. Organic indicators of groundwater pollution by a sanitary landfill. *Water Research* 20(9): 1153 (1986).

Augenstein, D. and J. Pacey. Landfill methane models. Presented at the 29th SWANA International Solid Waste Conference, Cincinnati, 1991.

Al-Yousfi, A. B. *Modeling of leachate and gas production and composition at sanitary landfills,* Pittsburgh, PA: University of Pittsburgh, PhD Thesis, 1992.

Augenstein, D., J. Pacey, R. Moore, and S. Thorneloe. Landfill methane enhancement. In: *Proceedings from the SWANA 16th Annual Landfill Gas Symposium,* GR-LG 0016, Louisville, KY, 1993, 21-48.

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

Baetz, B. W. and K. A. Onysko. Storage volume sizing for landfill leachate-recirculation systems. *Journal of Environmental Engineering* 119 (2): 378-383 (1993).

Bagchi, A. *Design, Construction, and Monitoring of Landfills.* John Wiley & Sons, Inc, New Yor, NY, 1994.

Barber, C., and P.J. Maris. Recirculation of leachate as a landfill management option: benefits and operational problems. *Q.J. Engineering Geology, London,* 17:19-29 (1984).

Barlaz, M.A., R.K. Ham, and D.M. Schaefer. Methane production from municipal refuse: a review of enhancement techniques and microbial dynamics. *Critical Reviews in Environmental Control,* 19(6): 557 (1990).

Bennett, G.F. Air quality aspects of hazardous waste landfills. *Journal of Hazardous Waste and Hazardous Materials,* 4(2): 119, (1987).

Bleiker, D. E., E. McBEan, and G. Farquhar. Refuse sampling and permeability Testing at the Brock West and keele Valley Landfills. presented at the Sixteenth International Madison Waste Conference, Madison, WI, September 22-23, 1993.

Bookter, T.J. and R.K. Ham. Stabilization of solid waste in landfills, *Journal of Environmental Engineering*, 108(6) 1089 (1982).

Brown, K.W. and K.C. Donnelly. An estimation of the risk associated with the organic constituents of hazardous and municipal waste landfill leachates. *Journal of Hazardous Wastes and Hazardous Materials*, 5(1): 3 (1988).

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

Buivid, M.G., D.L. Wise, M.J. Blanchet, E.C. Remedios, B.M. Jenkins, W.F. Boyd, and J.G. Pacey. Fuel gas enhancement by controlled landfilling of municipal solid waste. *Resources and Conservation*, 6: 3 (1981).

Campbell, D.J.V. UK Brogborough test cell project. In: *Landfill Gas Enhancement Test Cell Data Exchange, Final Report of the Landfill Gas Expert Working Group*. P. Lawson, ed., International Energy Agency, Harwell Laboratory, Oxfordshire, England, 1991.

Carra, J.S. and R. Cossu, ed. *International Perspectives on Municipal Solid Wastes and Sanitary Landfilling*. Academic Press, London, 1989.

Chian, E.S.K. Stability of organic matter in landfill leachates. *Water Research*, 11(2): 159, (1977).

Chian, E.S. and F.B. DeWalle. Characterization of soluble organic matter in leachate. *Environmental Science and Technology*, 11(2): 159, (1977).

Chian, E.S., DeWalle, F.B. Sanitary landfill leachates and their treatment. *Journal of Environmental Engineering* 102(EE2):411-431 (1976).

CMA Engineers, *Leachate Recirculation Annual Report*. Submitted to NHDES Waste Management Division, Portsmouth, NH, 1993.

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

Delaware Solid Waste Authority. *Test cell report, November, 1992 - May, 1993*. Central Solid Waste Management Center, Sandtown, Delaware, 1993.

DeWalle, F.B., E. S. K. Chian, and E. Hammerberg. Gas production from solid waste in landfills. *Journal of Environmental Engineering*, 104(EE3):415-432 (1978).

Doedens, H. and K. Cord-Landwehr. Leachate recirculation. In: *Proceedings Sardinia '91, ISWA International Sanitary Landfill Symposium*, Calgari, Italy, 1987.

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

EMCON. *Twelve-month extension Sonoma County solid waste stabilization study (final report).* GO6-EC-00351, San Jose, CA, 1976.

EMCON. *Controlled landfill project - fift annual report.* Project 343-03.02, San Jose, CA, 1987.

Fergusen, R.G. Sanitary landfilling in Canada. In: *International Perspectives on Municipal Solid Wastes and Sanitary Landfilling,* Carra, J.S. and R. Cossu, ed,. Academic Press, London, 1989.

Fletcher, P. Landfill gas enhancement technology - laboratory studies and field research. In: *Proceedings of Energy from Biomass and Wastes*, XIII, IGT, 1989. pp. 1001.

Franklin Associates, Ltd. *Characterization of municipal solid waste in the United States - 1994 Update.* prepared for the US Environmental Protection Agency EPA530/S-94/042, 1994.

Fungaroli, A. A. and R. L. Steiner. *Investigation of sanitary landfill behavior. EPA/6001/2-79*, 1979.

Giroud, J. P., A. Khatami, and K. Badu-Tweneboah. Evaluation of the rate of leakage through composite liners. *Geotextiles and Geomembranes*,8(4): 337-340 (1989).

Giroud, L.P. "Granular filters and geotextile gilters," *Proceedings of GeoFilters '96.* Lafleur, J. and Rollin, A. L., Editors, Montreal, Canada, 1996, pp 565-580.

Gonzales, A. J. "An integrated system for leachate reintroduction and gas venting." Presented at the 1994 GEOENVIRONMENT 2000 Conference, New Orleans, LA, USA, 1994.

Gould, J. P., W.H. Cross, and F. G. Pohland. Factors influencing mobility of toxic metals in landfills operated with leachate recycle. In: *Emerging Technologies in Hazardous Waste Management*, ed. D. W. Tedder and F. G. Pohland, ACS Symposium Series 422, 1989.

Gurijala, K. Rao. and J.M. Suflita. Environmental factors influencing methanogenisis from refuse in landfill samples. *Environmental Science & Technology,* 27(6):1176-1181 (1993).

Harmsen, J. Identification of organic compounds in leachate from a waste tip. *Environmental Science and Technology*, 17(6): 699 (1983).

Hartz, K.E., Klink, R.E., and R. K. Ham. Temperature effects: methane generation From landfill samples. *Journal of Environmental Engineering* 108(EE4):629-638 (1982).

IEA Expert Working Group on Landfill Gas. *Data Base of Landfill Test Cells.* 1995.

King, D. and A. Mureebe. Leachate management successfully implemented at landfill. *Water Environment and Technology* 4(9):42 (1992).

Klink, R.E. and R.K. Ham. Effect of moisture movement on methane production in solid waste landfill samples. *Resources and Conservation* 8: 29 (1982).

Koerner, G. R. and R. M. Koerner. Permeability of granular drainage material. Presented at the U.S. EPA Bioreactor Landfill Design and Operation Seminar, Wilmington Delaware, 1995.

Korfiatis, G. P. , A. C. Demetracopolous, E. L. Bourodimos, and E. G. Nawey. Moisture Transport in a Solid Waste Column. *Journal of Environmental Engineering,* 110(EE4):789-796 (1984).

Lagerkvist, 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., Oxfordshire, England: International Energy Agency, Harwell Laboratory, 1991a.

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

LaRegina, J. and J.W. Bozzelli. Volatile organic compounds at hazardous waste sites and a sanitary landfill in New Jersey. *Environmental Progress*, 5(1): 18 (1986).

Lechner, P., T. Lahner, and E. Binner. Reactor Landfill experiences gained at the Breitnau Research Landfill in Austria. Presented at the 16th International Madison Waste Conference, Madison, Wisconsin, 1993.

Leckie, J.O., J.G. Pacey, and C. Halvadakis. Landfill management with moisture control. *Journal of Environmental Engineering* 105(EE2): 337 (1979).

Lema, J.M., Mendez, R., and Blazquez, R. Characteristics of landfill leachates and alternatives for their treatment: a review. *Water, Air and Soil Pollution,* 40:223-250(1988).

Leszkiewicz, J. and P. McAulay. Municipal solid waste landfill bioreactor technology closure and post-closure. Presented at the US EPA Seminar - Landfill Bioreactor Design and Operation, New York Energy Research and Development Authority. *Enhancement of Landfill Gas Production, Nanticoke Landfill, Binghamton, New York.* NYSERDA Report 87-19, Wehran Engineering, July, 1987.

Noble, J.J. and A.E. Arnold. Experimental and mathematical modeling of moisture transport in landfills. *Chemical Eng. Comm.* 100:95-111 (1991).

Oman, Cecilia and P.Hynning. Identification of organic compounds in municipal landfill leachates. *Environmental Pollution* 80: 265-271 (1993).

Otieno, F.O. Leachate recirculation in landfills as a management technique. In: *Proceedings of Sardinia '89, Second International Landfill Symposium*, Calgari, Italy, 1989.

Oweis, I. and Khera R. Criteria for geotechnical construction of sanitary landfills. in *Int. Symp. on Envir. Geotech.*, H. Y. Fang, ed., Lehigh Univ. Press, Bethlehem, PA, 1986, 205-222.

Oweis, E.S., D. A. Smith, R. B. Ellwood, and D. S. Greene. Hydraulic characteristic of municipal refuse. *ASCE J. Geotechnical Eng.*, 116(4): 539-553 (1990).

Owens, J. M. and D. P. Chynoweth. Biochemical methane potential of MSW components. Presented at the International Symposium on Anaerobic Digestion of Solid Waste, Venice, Ital, April 15 - 17, 1992.

Pacey, J.G., J.C. Glaub, and R.E. Van Heuit. Results of the Mountain View controlled landfill project. In: *Proceedings of the GRCDA 10th International Landfill Gas Symposium,* GRCDA, Silver Spring, Maryland, 1987.

Palumbo, D. *Estimating Early MSW Landfill Gas Production.* MS Thesis, University of Central Florida, Orlando, Florida, 1995.

Pohland, F.G. *Sanitary Landfill Stabilization with Leachate Recycle and Residual Treatment.* U.S. Environmental Protection Agency, Cincinnati, Ohio, EPA-600/2-75-043, 1975.

Pohland, F.G. Leachate recycle as landfill management option. *Journal of Environmental Engineering* 106(EE6):1057-1069 (1980).

Pohland, F. G., S. R. Harper, K. Chang, J. T. Dertien, and E. S. K. Chian. Leachate generation and control at landfill disposal sites. *Water Pollution Research Journal of Canada 20(3): 10-24 (1985).*

Pohland, F.G. and S.R. Harper. *Critical Review and Summary of Leachate and Gas Production From Landfills.* EPA/600/2-86/073, US Environmental Protection Agency, Cincinnati, OH, 1986.

Pohland, F.G., W.H. Cross, J.P. Gould, and D.R. Reinhart. *The Behavior and Assimilation of Organic Priority Pollutants Codisposed with Municipal Refuse*. USEPA, EPA Coop. Agreement CR-812158, Volume 1, 1992.

Pohland, F.G. *Assessment of Solid Waste and Remaining Stabilization Potential after Exposure to Leachate Recirculation at a Municipal Landfill*. Prepared for Post, Buckley, Schuh & Jernigan, Inc, Project No. 07-584.18, 1992.

Rattray, T. Demographics and dscards. *Garbage* 4(6): 27 (1993).

Rees, J.F. Optimisation of methane production and refuse decomposition in landfills by temperature control. *J. Chem. Tech. Biotechnol.* 30: 458-465 (1980).

Reinhardt, J.J. and R.K. Ham. *Solid Waste Milling and Disposal on Land without Cover*. U.S. Environmental Protection Agency, Cincinnati, Ohio, PB-234 930, 1974.

Robinson, H.D. and P.J. Maris. The treatment of leachates from domestic waste in landfill sites. *Journal of Water Pollution Control Federation* 57(1): 30 (1985).

Rovers, F.A. and G.J. Farquhar. Infiltration and landfill behavior. *Journal of Environmental Engineering* 99(10): 671-690 (1973).

Sawney, B.L. and R.P. Kozloski. Organic pollutants in leachates from landfill sites. *Journal of Environmental Quality* 13(3): 349 (1984).

Schultz, B. and P. Kjeldsen. Screening of organic matter in leachate from sanitary landfills using gas chromatography combined with mass spectrometry. *Water Research* 20(8): 965 (1986).

Siu, W, D. A. Levaggi, and T. F. Brennan. Solid waste assessment test results from landfills in the San Francisco Bay area. Presented at the 82nd Annual meeting and Exhibition of the Air and Waste Management Association, Anaheim, CA, 1989.

Stegmann, R. and H.H. Spendlin. Enhancement of degradation: German experiences. In: *Sanitary Landfilling: Process, Technology and Environmental Impact*. Ed.: T.H. Christensen, R. Cossu, and R. Stegmann, Academic Press, London, 1989.

Sulfita, J., C. Gerba, R. Ham, A. Palmisano, W. Rathje, and J. Robinson. The world's largest landfill. *Environmental Science & Technology* 26(8):1486-1495 (1992).

Tchobanoglous, G., H. Theisen, and S.A. Vigil, *Integrated Solid Waste Management: Engineering Principles and Management Issues*. McGraw-Hill, Inc., New York, NY, 1993.

ten Brummeler E.T., C.J. Horbach, and I.W. Koster. Dry anaerobic batch digestion of the organic fraction of municipal solid waste. *Journal of Chem. Tech. and Biotechnology* 50:191-209 (1991).

Tittlebaum, M.E. Organic carbon content stabilization through landfill leachate recirculation. *Journal of Water Pollution Control Federation* 54: 428 (1982).

Townsend, T.G. *Assessment and Conceptual Design of an On-Site Leachate Treatment System Using Leachate Recycle, Membrane Seperation and Land Application.* MS Thesis, University of Florida, Gainesville, 1992.

Townsend, T. G. *Leachate Recycle at the Southwest Landfill Using Horizontal Injection.* PhD Thesis, University of Florida, Gainesville, 1994.

U.S. Environmental Protection Agency. Solid waste disposal facility criteria; proposed rule. *Federal Register,* 53(168) 33313 (1988b).

U.S. Environmental Protection Agency. *Requirements for Hazardous Waste Landfill Design, Contruction, and Closure.* Office of Research and Development, Cinccinnati, OH, EPA/625/4-89/022, 1989.

U.S. Congress, Office of Technology Assessment. *Facing America's Trash: What Next for Municipal Solid Waste?* Office of Solid Waste and Emergency Response, Washington, D.C., PB90-174897, 1990.

US Environmental Protection Agency. *Report to Congress. Solid Waste Disposal in the United States.* EPA/530-SW-88-011B, Office of Solid Waste and Emergency Response, Washington, D.C., 1988a.

Venkataramani, E.S., Ahlert, R.C., and Corbo, P. Biological treatment of landfill leachates. *CRC Critical Reviews in Environmental Control,* 14(4):333-372 (1986).

Watson, R. State of Delaware's case history review: a full scale active waste management approach. Presented at the Modern Double Lined Landfill Management Seminar, Saratoga Springs, New York, 1993.

Wehran Engineering, P.C. & Dynatech Scientific, Inc. *Enhancement of Landfill Gas Production, Nanticoke Landfill, Binghamton, New York.* New York State Energy Research and Development Authority, NYSERDA Report 87-19. July, 1987.

Willumsen, H.C. 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., Oxfordshire, England: International Energy Agency, Harwell Laboratory, 1991.

Wood, J.A. and M.L. Porter. Hazardous pollutants in Class II landfills. *Journal of the Air Pollution Control Association.* 37(5): 609, (1987).

Young P.J. and A. Parker. The identification and possible environmental impact of trace gases and vapors in landfill gas. *Waste Management and Research,* 1: 213 (1983).

Appendix A

Survey of State Regulations - Leachate Recirculation

ALABAMA

Contact: Solid Waste Branch, Department of Environmental Management
(205) 271-7771

State regulations do not prohibit recirculation, however no landfills are practicing recirculation in the state at present. The State would entertain the concept if an application is presented.

ALASKA

Contact: Department of Environmental Quality, Solid and Hazardous Waste Section
(907) 465-5150

Alaska is currently (Fall 1992) in the process of revising solid waste regulations to comply with the RCRA Subtitle D requirements. Leachate recirculation is not specifically addressed in existing regulations, however, it is allowable under either the existing or proposed regulations. No one in the State has tried leachate recirculation.

ARIZONA

Contact: Office of Waste Programs, Arizona Department of Environmental Quality
(602) 207-2300

No State regulations currently address recirculation of leachate. Landfills in the state do not report any leachate production. If proposed, recirculation would be possible, if a leachate collection system is available. Aquifer monitoring has not detected problems with leachate contamination.

ARKANSAS

Contact: Solid Waste Division
(501) 562-6533

Leachate recirculation is permitted although regulations do not specifically address it. Facilities would be required to meet Subtitle D requirements as a minimum. They are planning to rewrite regulations soon (per March 16, 1993 conversation). One system has been designed to pump leachate back through the landfill using a system of horizontal perforated pipes.

CALIFORNIA

Contact: Yolo County
(916) 666-8775

Regulations addressing leachate recirculation are regionally specific. State Regulatory Water Quality Control boards issue waste discharge permits to landfills. The Integrated Waste Management Board regulates through Title 14 (CA) and Subtitle D closure and design of landfills.

COLORADO

Contact: Hazardous Materials and Waste Management Division
(303) 692-3447

The state has a dry climate, therefore, leachate generation indicates a design problem. No leachate production is the objective. The state added RCRA Subtitle D regulations to draft regulations for leachate recirculation, so, if desired, it can implement but the design must be appropriate. The present two ft clay liner cannot accept leachate recirculation. Leachate at one landfill is carbon treated and irrigated for top growth, but an impermeable cover provided.

CONNECTICUT

Contact: Waste Management Bureau
(203) 566-5847

No official policy regarding recirculation exists. No one is practicing it, particularly considering there are no lined landfill operating in the state. The trend in Connecticut is to eliminate landfills, to recover 2/3 of the MSW, and burn the rest. They are exporting a small amount of MSW and C/D at present. Small C/D and ash landfills will be used. Ash monofills will be lined.

DELAWARE

Contact: Delaware Department of Natural Resources and Environmental Control, Hazardous Waste Management Branch
(302) 739-8320

Leachate recirculation is permitted on a case by case basis. There are no specific requirements for recirculation in the regulations. One facility (DSWA) is recirculating at present.

FLORIDA

Contact: Solid Waste Management, Department of Environmental Regulation
(904) 922-6104

Leachate recirculation is permitted if leachate was derived from the landfill and the landfill is designed in accordance with provisions in the FAC which generally require a composite or double liner. Recirculation is practiced at many sites around the state.

GEORGIA

Contact: Georgia Environmental Protection Division
(404) 362-2692

Leachate recirculation is regulated under Chapter 391-3-4 and the Municipal Solid Waste Landfill Liner Design Criteria. Recirculation is allowed on a case by case basis. Criteria include: the area must have been previously filled with solid waste, sufficient waste capacity to absorb the leachate must be present, an approved piping system located under an intermediate cover layer, no odors, runoff or ponding. No spraying of untreated leachate is permitted.

IDAHO

Contact: Department of Health & Welfare, Division of Environmental Quality
(208) 334-5860

Idaho does not have specific regulations addressing recirculation, but Subtitle D is followed, so the state will permit recirculation. One landfill (Eastside) has applied for permitting with recirculation, but has not been constructed yet. A second site (Fighting Creek Landfill) designed by Parametrics will start up in May 1993.

ILLINOIS

Contact: Illinois EPA
(217) 782-6760

Leachate recirculation is permitted, design requirements include provision for clean out of recirculation pipes. Several landfills have attempted recirculation but discontinued the practice because of clogging.

INDIANA

Contact: Office of Solid and Hazardous Waste
(317) 232-8840

Regulations state that if approved by the commissioner, recirculation is possible. The site must have adequate controls. No sites are presently recirculating. Several demonstration projects attempted recirculation but were discontinued due to improper design. Guidance exists to permit recirculation if a good liner is provided.

IOWA

Contact: Iowa Department of Natural Resources
(515) 281-5145

Iowa permits leachate recirculation if a state-of-the-art leachate collection system is provided beneath the recirculation area, including 4 ft of clay. Two sites are recirculating at present. Four to six ash monofills use co-combustion leachate to wet fly ash to control dust.

KANSAS

Contact: Bureau of Waste Management
(912) 296-1596

Leachate recirculation is not address specifically in regulations, however the regulations are being rewritten to conform with Subtitle D (1/93). If asked, the state will view leachate recirculation favorably. It appears to be a good approach.

KENTUCKY

Contact: Division of Waste Management, Kentucky Natural Resource and Environmental Protection
(502) 564-6716

Leachate recirculation is not presently addressed in regulations, but regulations are being rewritten to incorporate Subtitle D. More stringent liner requirements will be in effect at that point. At present no liner requirement is in force. The state will negotiate with US EPA in October of 1993 for solid waste program authorization.

LOUISIANA

Contact: Louisiana Department of Environmental Quality
(504) 765-0261

Existing regulations do not address leachate recirculation, however, permits can be issued with leachate recirculation. Proposed regulation (2/93) will not permit leachate recirculation. "Leachate shall not be managed by allowing it to be absorbed by waste." Subsection 7.11 B4 SW05. The state is concerned about the safety of leachate recirculation considering the geology and climate of the state.

MAINE

Contact: Bureau Hazardous Materials and Solid Waste Control, Statehouse, Station 17, Augusta, Maine
(207) 289-2651

No one has tried leachate recirculation in the state. Regulations would allow recirculation if justified and design meets requirements. Leachate recirculation is not specifically addressed in regulations.

MARYLAND

Contact: Hazard and Solid Waste Management Administration
(410) 631-3364

State regulations are more flexible than Subtitle D regulations. Where leachate recirculation is practiced, the landfill must meet Subtitle D Regulations. Two landfills are recirculating, the Central Landfill at the Eastern Shore and the Mid Shore Landfill . They practice a case by case analysis policy.

MASSACHUSETTS

Contact: Department of Environmental Protection, Bureau of Waste Prevention
(617) 292-5974

Leachate recirculation is permitted, regulations do not preclude it. Nothing specifically addressing recirculation is in the regulations. The issue has not come up to date. There was a limited request years ago but it did not go anywhere. A lined facility would be required.

MICHIGAN

Contact: Waste Management Division, Department of Natural Resources
(517) 373-9523

Leachate recirculation is allowed according to regulations. Proof of no contamination at the site and a "good" liner/leachate collection system must be provided. Concern was expressed over liner leakage resulting in groundwater contamination. Recirculation may increase head on liner, but in the long run, recirculation should result in less pollution. New liner standards are under development which are more restrictive than RCRA Subtitle D. The state is starting to look at recirculation in designs as well as gas collection during active phases for odor control.

MINNESOTA

Contact: Minnesota Pollution Control Agency
(612) 296-7300

Regulations prohibit leachate recirculation. There is n interest in the state at present. Recirculation would not work in the winter in Minnesota due to freezing problems.

MISSISSIPPI

Contact: Mississippi Department of Environmental Quality
(601) 961-5171

Regulations do not address leachate recirculation. The present regulations will change considerably in early 1993, primarily adopting Subtitle D requirements. Recirculation would be permitted as a backup to on-site treatment. No landfill is presently practicing leachate recirculation in the state.

MISSOURI

Contact: MSW Program, Division of Environmental Quality, Missouri Department of Natural Resources
(314) 751-3176

Leachate recirculation will be permitted using beefed up criteria (liner and leachate collection system above minimum standards). The first landfill using recirculation by injection manholes went into operation in 1993.

Regulations prohibit recirculation at present. New Jersey is trying to develop a test site to explore recirculation. Primitive attempts at spraying with agricultural sprinkler systems have had odor and aerosol problems.

NEW MEXICO

Contact: (505) 827-0197

Leachate recirculation is not addressed, nor is it precluded. The state might have some concerns with liquids introduced to the landfill. A couple of facilities are using ponds for evaporation but no one is recirculating leachate.

NEW YORK

Contact: NY Department of Environmental Conservation
(518) 457-2051

Regulations 360-2, promulgated in November 1992 address leachate recirculation. Leachate recirculation is prohibited unless the landfill meets the following requirements: permitted, groundwater monitoring data verifies no landfill induced contamination, double liner, demonstration of six months of acceptable primary liner performance, no recirculation where soil cover applied unless provisions for runoff collection and containment provided, and does not increase primary liner systems leakage beyond 20 gal/acre-day.

NORTH CAROLINA

Contact: Division of Solid Waste Management
(919) 733-0692

North Carolina is receptive to the idea of leachate recirculation and is participating in several projects investigating the process.

NORTH DAKOTA

Contact: (701) 221-5166

Regulations specify that the facility must have a composite liner and leachate collection system if recirculation is practiced. No facilities recirculate at present.

OHIO

Contact: (614) 644-3020

Regulations do not permit leachate recirculation.

OKLAHOMA

Contact: (405) 271-8135

Few landfills are operating in the state with liners and leachate collection systems due to low precipitation. Regulations do not address recirculation. New landfills will be regulated on a case by case basis.

OREGON

Contact: (503) 229-5913

Regulations do not specifically address recirculation, however, for all practical purposes, recirculation is not permitted. Entombment seems to be the intention of the state at present.

PENNSYLVANIA

Leachate recirculation has been allowed since 1988. Four requirements exist: double liner system, the recirculation system constructed under an interim cover with piping system, odor production prevented, and leachate outbreak or runoff controlled. Recirculation is used at Lycoming County and other sites as a backup leachate management system.

RHODE ISLAND

Contact: Division of Air & Hazardous Material
(401) 277-2797

Regulations do not address leachate recirculation. A variance is required as well as a leachate collection system. There is room for variance; they are not opposed to using leachate recirculation. No landfill has applied for a variance.

SOUTH CAROLINA

Contact: So. Carolina Bureau of Solid and Hazardous Waste Management
(803) 734-5200

New regulations have been proposed which should be in force by 1994. Recirculation can occur in special cases where an emergency situation exists (such as an inability to take leachate off site) for a maximum of 30 days. The opinion is that conditions in this area are not conducive to leachate recirculation. No design requirements are in effect. One or two facilities have proposed leachate recirculation but no one has attempted it.

SOUTH DAKOTA

Contact: Department of Environmental and Natural Resources
(605) 773-3153

Regulations do not presently address leachate recirculation. Because of low precipitation rates, leachate management is not an issue. No MSW leachate collection system is in place in the state. If requested, an amendment to the permit could be provided to accommodate recirculation.

TENNESSEE

Contact: Division of Solid Waste Management
(615) 532-0804

The regulations briefly address leachate recirculation, permitting it with special approval, but only where a synthetic liner is provided. Recirculation is not presently practiced at a sanitary landfill. Several industrial sites have sprayed leachate on the landfill as well as adjacent land with mixed results. The state would consider permitting recirculation.

TEXAS

Contact: MSW Division, Texas Water Commission
(512) 908-6787

Presently (2/93) the state is in the process of rewriting regulations, to be published within the next few weeks. Regulations will implement Subtitle D. Leachate recirculation is permitted at present. Several landfills are recirculating via spraying on the working face to facilitate evaporation.

UTAH

Contact: Division of Solid and Hazardous Waste, Department of Environmental Quality
(801) 538-6170

Utah is in the process of revising regulations to incorporate Subtitle D. Regulations should take effect on April or May 1993. Regulations will permit return of leachate only to areas where a composite liner is provided. No one has proposed leachate recirculation. No leachate production to speak of in

Utah since precipitation is low except in mountains where landfills are not sited.

VERMONT

Contact: Solid Waste Division, Vermont Department of Environmental Conservation
(802) 244-7831

There is no specific reference in regulations to leachate recirculation. Design guidance is available which allows recirculation. No landfill is currently recirculating although several conceptual designs are considering it.

VIRGINIA

Draft regulations identify leachate disposal preferences, including leachate recirculation"... provided that the irrigated area is underlain by a composite liner and that the operation causes no odors, runoff or ponding..."

WASHINGTON

Contact: Washington State Department of Ecology, Solid and Hazardous Waste Program
(206) 459-6316

Leachate recirculation is not allowed at present. A liquid ban in place (except for condensate). As a result of EPA rule making they will allow recirculation with EPA conditions plus additional restrictions. Design must address clogging, settlement, and other quality factors. They are developing an issue paper available May 1993.

WEST VIRGINIA

Contact: Department of Commerce, Labor and Environmental Resources, Division of Natural Resources
(304) 558-6350

Regulations permit recirculation, but the state does not like it. A few landfills are recirculating via spraying using perforated hoses. The opinion was expressed that recirculation does not accomplish much in the way of evaporation. A composite liner with a leachate detection zone required. Plans are to outlaw recirculation when regulations are rewritten to adopt Subtitle D.

WISCONSIN

Contact: Solid Waste Management, Wisconsin DNR
(608) 266-0833

Leachate recirculation has not been permitted for some time. The state does not accept the concept that leachate treatment is accomplished via recirculation. When done in the 70's and 80's operators were only trying to avoid treatment and many problems ensued with leachate seepage. The absorptive capacity predicted does not seem to exist. Concerns exist over penetration and seepage of leachate through liner as well as consequences of gas production during accelerated decomposition. Weather conditions are a minor concern.

WYOMING

Contact: Solid Waste Management Program
(307) 777-7752

The regulations do not address recirculation since leachate is not produced.

Appendix B

Analysis of Chronological COD Data

Unfortunately, the relative efficacy of leachate recirculation in enhancing waste degradation relative to conventionally operated landfills at full-scale is difficult to quantify, because of the lack of conventional/recirculation parallel operations. Recognizing this limitation, leachate COD data were gathered from the literature for conventional landfills. These data and their sources follow and are plotted in Figure B-1. The data are discussed in detail in Chapter 6.

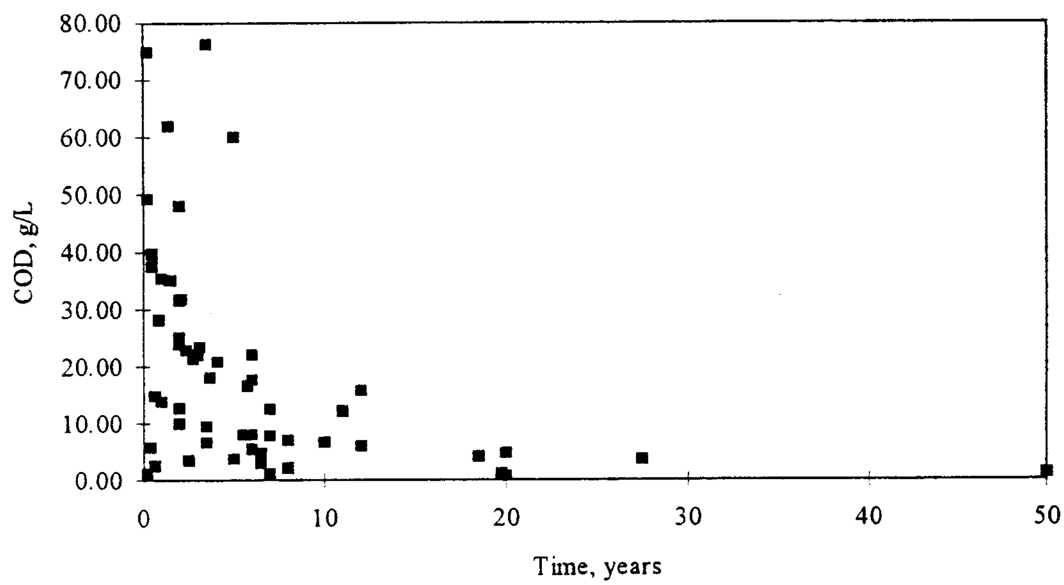


Figure B-1. Leachate COD from conventional landfills.

TABLE B-1. CONVENTIONAL LANDFILL COD DATA

Landfill Age, Years	COD, mg/l	Reference
0.25	49300	Chian and Dewalle, 1977
0.25	1180	Polk County, FL
0.4	5767	Wigh, 1979
0.5	39680	Hughes, et al, 1971
0.5	37500	Wigh, 1979
0.65	14891	Wigh, 1979
0.67	2556	Wigh, 1979
0.9	28115	Wigh, 1979
1	13800	Henry, et al, 1987
1	35350	Lema, et al, 1988
1.4	61991	Wigh, 1979
1.5	35000	Wigh, 1979
2	25000	Wigh, 1979
2	31600	Bekker and Kaspers, 1981
2	12602	SCS Engineers, 1976
2	48000	Lema, et al, 1988
2	23800	Robinson and Maris, 1985
2	10000	Lema, et al, 1988
2.1	31824	Wigh, 1979
2.35	22838	Wigh, 1979
2.5	3455	Johansen and Carlson, 1976
2.77	21388	Wigh, 1979
3	22000	Lema, et al, 1988
3.1	23407	Wigh, 1979
3.5	76300	Meichtry, 1971
3.5	6675	Reinhardt and Ham, 1973
3.68	18085	Wigh, 1979
4.1	20836	Wigh, 1979
5	60000	Harmsen, 1983
5	3800	Henry, et al, 1987
5.5	8000	Hughes, et al, 1971
5.75	16592	SCS Engineers, 1976
6	8000	Hughes, et al, 1971
6	5491	Ministry, 1961
6	22000	Lema, et al, 1988

Landfill Age, Years	COD, mg/l	Reference
6	17662	SCS Engineers, 1976
6.5	3042	Meichtry, 1971
6.5	4757	SCS Engineers, 1976
7	1200	Kelly, 1987
7	1250	Schultz and Kjeldsen, 1986
7	7789	SCS Engineers, 1978
8	7000	Harmsen, 1983
8	2100	Oman and Hynning, 1991
9	3000	Ehrig, 1983
10	6700	Schultz and Kjeldsen, 1986
11	12100	Schultz and Kjeldsen, 1986
12	6000	Schultz and Kjeldsen, 1986
12	15750	Schultz and Kjeldsen, 1986
18.5	4100	Lema, et al, 1988
19.75	1200	Lema, et al, 1988
20	4792	SCS Engineers, 1978
27.5	3631	SCS Engineers, 1978
50	1198	SCS Engineers, 1978

Appendix B. References

deBekker, P. and H. Kaspers. Anaerobic treatment of leachate from controlled tips of municipal solid waste. In: *Proceedings of the Fifth European Sewage and Refuse Symposium*, Munich, Germany, 1981.

Chian, E. and F. Dewalle. Sanitary landfill leachates and their treatment, Journal of Envionmental 102: 411-31 (1976).

Depuydt, Kent T., A. Higgins, and R. Simpkins. *Innovation Technolgies for Solid Waste Management and Leachate Treatment at The Burlington County*, NJ Resource Recovery Facilities Complex. Canadian Waste Management/ Waste Tech'91 Conferenece, October 30 to November 1, 1991.

Ehrig, H. J. Leachate quality. *In Sanitary Landfilling: Process, Technology and Environment Impact*, ed. T. Christensen, R. Cossu & R. Stegmann. Acadimic Press, London, 1989. pp. 213-29.

Ehrig, H. J.. Quality and quantity of sanitary landfill leachate. *Waste Management Resources* 1: 53-68, 1983.

Harmsen, J. Identification of organic compounds in leachate from a waste tip. *Environmental Science and Technology* 17(6): 600 (1983).

Henry, J. G. New developments in landfill leachate treatment. In: *Proceedings of New Directions and Research in Waste Treatment and Residuals Management,* Univ. of British Columbia, Canada, 1985, p 139.

Hughes, G. M., R. A. Landon, and R. N. Farvolden. *Hydrogeology of Solid Waste Disposal Sites in Northeastern Illinois.* SW-12d, U. S. Environmental Protection Agency, Washington, D. C., 1971.

Johansen, O. J. and D. A. Carlson. Characterization of sanitary landfill leachates, *Water Research.* 10:1129-1134 (1976).

Kelly, J. G. Pilot testing for combined treatment of leachate from a domestic waste landfill site. *J. of Water Pollution Control Federation* 40: 223.

Lema, J.M., Mendez, R., and Blazquez, R. Characteristics of landfill leachates and alternatives for their treatment: a review. *Water, Air and Soil Pollution,* 40:223-250(1988).

Lu, James C. S. , B. Eichenberger, and R.J. Stearns. *Leachate from Municipal Landfills: Production and Management, Pollution Technology Review No. 119*, Calscience Research, Inc., Noyes Publications, New Jersey, U. S. A., 1985.

Meichtry, T. M. Leachate control system. Presented at Los Angeles Regional Forum on Solid Waste Management, 1971. pp. 20.

Oman, Ceceliaa and Per-Ake Hynning. Identification of organic compounds in municipal landfill leachates. *Environmental Pollution* 80: 265-271 (1991).

Reinhardt, J. J., and R. K. Ham. *Final Report on a Demonstrated Project at Madison, Wisconsin, to invistigate Milling of Solid Wastes Between 1966 and 1972,* Vol. 1. U. S. Environmental Protection Agency, Office of Solid Wastes Management Program, Washington, D. C., 1973.

Robinson, H.D. and P.J. Maris. The treatment of leachates from domestic waste in landfill sites. *Journal of Water Pollution Control Federation* 57(1): 30 (1985).

Schultz, B. and P. Kjeldsen. Screening of organic matter in leachates from sanitary landfills using Gas chromatography combined with mass spectrometry. *Water Research* 20(8): 965-969 (1986).

SCS Engineers, *Investigation of Ground-Water Contamination from Subsurfaces Sewage Sludge Disposal Volume II, Case Study Reports.* EPA 530/SW-167C, U. S. Environmental Protection Agency, Washington, D. C. 1976.

SCS Engineers, *The Selection and Monitoring of Land Disposal Case Study Sites. Volume I. Project Description and Findings.* Contract Number 68-01-2973, U. S. Environmental Protection Agency, Washington, D. C., 1976.

Wigh, Richard, *Boone County Field Site Interim Report: Test Cells 2A, 2B, 2C, and 2D*, U. S. A. Environmental Protection Agency, Regional Services Corporation, Inc., Ohio, 1979.

Appendix C

Hydrodynamic Modeling of Leachate Recirculating Landfills

Philip T. McCreanor and Debra R. Reinhart

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

Abstract

Leachate recirculation is an emerging technology for the enhanced stabilization of active landfills and in situ treatment of problematic landfills. A variety of researcher have documented the benefits of increasing landfill moisture content and liquid movement through the fill. However, little work has addressed the hydrodynamic characteristics of the recirculating landfill, specifically the effect of leachate flow rate and waste characteristics upon leachate routing. This paper presents the results of mathematical modeling of the horizontal infiltration trench and vertical infiltration well, two commonly employed leachate application methods. From transient modeling, it was found that the vertical well is inefficient at wetting the upper portion of thelandfill while the horizontal trench was less effective at wetting the lower portion of the fill, suggesting a combination of the two devices would be the most efficient means of recirculating leachate.

Keywords

Leachate, recirculation, hydrodynamics, modeling, infiltration trench, infiltration well, impact area.

Introduction

The contamination of groundwater by landfill leachates has been recognized by a variety of researchers (Reinhard, *et al*, 1984; Schultz and Kjeldsen, 1986; Sawney and Kozloski, 1984). Organic chemicals found in 58 municipal and industrial landfill leachates represented a broad range of chemicals with significant genotoxic potential (Brown and Donnelly, 1988). Some 22 percent of the sites placed on the US National Priority List for hazardous waste site cleanup are closed municipal landfills (Repa, 1988). Groundwater is the primary contaminant release route at these sites. Remediation at problematic landfill sites is generally accomplished using source containment (usually via capping) along with groundwater pump and treat systems. It is widely recognized, however, that without source removal, pump and treat techniques merely prevent plume migration and generally cannot provide complete, long-term site restoration.

Leachate recirculation, an innovative remediation technique, has been proposed at two problematic municipal landfill sites, including one superfund site (Harper, 1993; Harper, 1995). Leachate recirculation involves the return of moisture emanating from an active or closed site to the landfill. Recirculation provides a means of optimizing environmental conditions within the landfill to provide enhanced stabilization of landfill contents as well as treatment of moisture moving through the fill. Leachate recirculation has application both to active landfill sites, providing a means of leachate management and accelerated stabilization of waste; as well as to problematic sites, where plume containment, in situ groundwater treatment, and source reduction can be simultaneously accomplished. Leachate recirculation is discussed in more detail elsewhere (Pohland, 1995).

Implementation of leachate recirculation requires an understanding of the effect of leachate recirculation on microbially mediated processes and reactions and of the hydrodynamics of leachate flow within a landfill, including moisture distribution, effects on leachate collection systems, and optimum operating strategy. While full-scale data are slowly becoming available, a more thorough consideration of the many parameters impacting the technology necessitates use of a mathematical model.

This paper presents the results of transient, unsaturated flow modeling of two commonly employed leachate recirculation devices; the vertical leachate infiltration well and the horizontal infiltration trench. These methodologies were selected based on their widespread use and their compatibility with the final closure of the landfill. The horizontal infiltration trench is generally constructed as shown in Figure C-1. A perforated PVC pipe is surrounded by gravel or tire chips. In order to prevent the migration of the gravel or tire chips and to maintain the trench integrity, a geotextile or sand layer often bounds the trench. To inhibit the upward flow of leachate, a clay layer or prefabricated vertical infiltrator may top the trench.

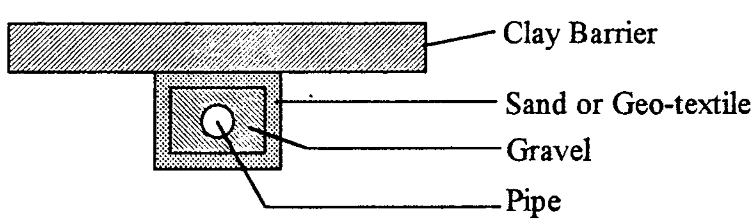


Figure C-1. Horizontal leachate infiltration trench.

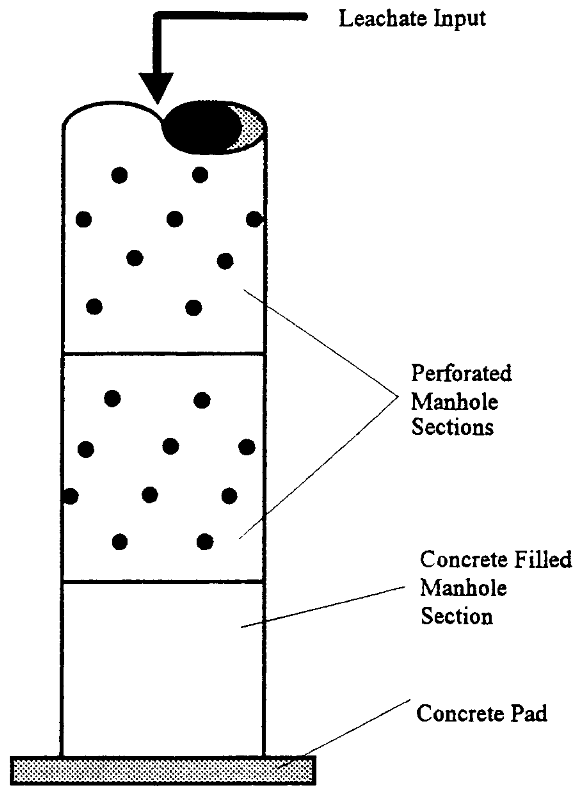


Figure C-2. Vertical leachate recirculation well.

The vertical infiltration well (Figure C-2) is composed of a series of gravel-filled perforated manhole sections which are stacked on top of a concrete-filled manhole section. The entire structure is placed on a concrete pad for stability. The vertical infiltration well is generally operated in a fill and drain manner. A single well is filled to capacity permitted to drain. Then the filling operation moves to the next well which is in turn filled to capacity, and so forth.

Methodology

A United States Geological Survey (USGS) model for Saturated and Unsaturated flow and TRAnsport, SUTRA (Voss, 1984, Voss, 1991), was used to model the recirculating landfill. SUTRA uses a two-dimensional hybrid finite element and integrated finite difference method to approximate the governing equations of flow and transport. SUTRA is capable of performing steady-state and non steady-state simulations. Modeling proceeded in two phases; steady-state modeling to perform an initial screening of SUTRA capabilities and to identify further data requirements, and transient modeling following extensive modifications to SUTRA.

The primary inputs to SUTRA are the physical characteristics of both the solid matrix and fluid, porosity, permeability, dispersivity, and the unsaturated flow characteristics. Porosity is input on a node-wise basis while permeability and dispersivity are input by element. The basis of the SUTRA simulation is a mesh of nodes in cartesian coordinates which are then connected to form quadrilateral elements. In addition, the impact of waste heterogeneity and gas production on fluid flow are under consideration. Output from the model provides degree of saturation (volume of water/volume of voids), fluid mass budgets, and depth of the head on the landfill liner as a function of the rate of leachate introduction and location of recirculation device(s).

The power equations (Equations C-1a and C-1b) proposed by Korfiatis, et al (1984) were used to model the unsaturated characteristics of the waste matrix. Korfiatis determined the saturated suction head to be 6 cm of water for municipal solid waste. The Brooks and Corey equations with appropriate parameters were used to model the sand and gravel components of the model (Lappala, et al, 1987).

$$k_r = \left(\frac{h}{h_S}\right)^{-2.75} \tag{C-1a}$$

$$\theta = \left(\frac{h}{h_S}\right)^{4} \tag{C-1b}$$

where:

k_r	=	relative hydraulic conductivity, unitless
θ	=	volumetric moisture content, wet basis, V/V
h_S	=	saturation suction pressure, $ML^{-1}T^{-2}$
h	=	suction pressure, $ML^{-1}T^{-2}$

During exploratory steady state modeling it was determined that SUTRA required several modifications in order to be capable of transient modeling of leachate recirculation. Programming changes included:

- adding a pressure-based variable removal boundary condition,
- adding unsaturated relationships more appropriate to modeling solid waste,
- reformatting output routines and files, and
- recompiling the code for use on UNIX systems.

These changes were directed at easing data analysis, enabling transient simulations of leachate recirculation components including the leachate collection system, and allowing the direct use of commonly accepted equations for unsaturated relationships in solid waste.

The modeling of the infiltration trench consisted of placing discrete fluid sources directly within the waste matrix (see Figure C-1). The gravel/tire chip and geo-textile materials commonly used within the trench were not modeled due to dimensionality constraints and to simplify the construction of the required input files. The recirculation rates modeled were 2.0, 4.0, 6.0, and

8.0 m^3/day/m of trench which bracket reported operating ranges of horizontal infiltration trenches (Miller, et al., 1993). Transient simulations of single and multiple horizontal injection lines have been conducted for a conductivity of 10^{-3} cm/s and a landfill depth of 15 m.

The modeling of the vertical infiltration well (see Figure C-2) consisted of using a radial coordinate system and placing a series of fluid sources vertically from a level of 2 m to 13 m, discharging directly into the waste. Simulation of recirculation rates of 0.20, 0.40, and 0.80 m^3/day at a hydraulic conductivity of 10^{-3} cm/s and a landfill depth of 15 m were conducted. It was also necessary to model the effect of increasing fluid pressure with depth within the well on discharge rate. This was accomplished by using "stepped" nodal fluxes as shown in Figure C-3.

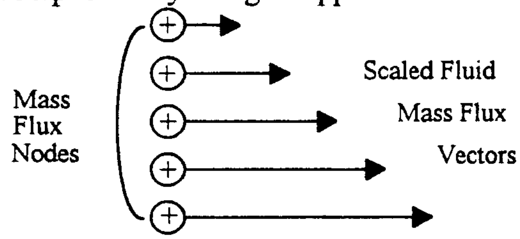


Figure C-3. Simplified example of flux nodes which simulate the vertical well.

The intent of the stepped approach shown in Figure C-3 was to simulate the effect of the variation of discharge velocities with depth along the well. First, an incremental flux unit was calculated as shown in Equation C-2.

$$q' = \frac{q}{\sum_{i=1}^{n} i} \qquad \text{(C-2)}$$

where:

q'	=	incremental flux unit, MT^{-1}
q	=	total flow to well, MT^{-1}
n	=	the number of nodes used to simulate e well flow
i	=	integer

Then the well discharge nodes were numbered from the top down beginning with one. The individual nodal discharges were calculated as in Equation C-3.

$$q_m = m \cdot q' \qquad \text{(C-3)}$$

where:

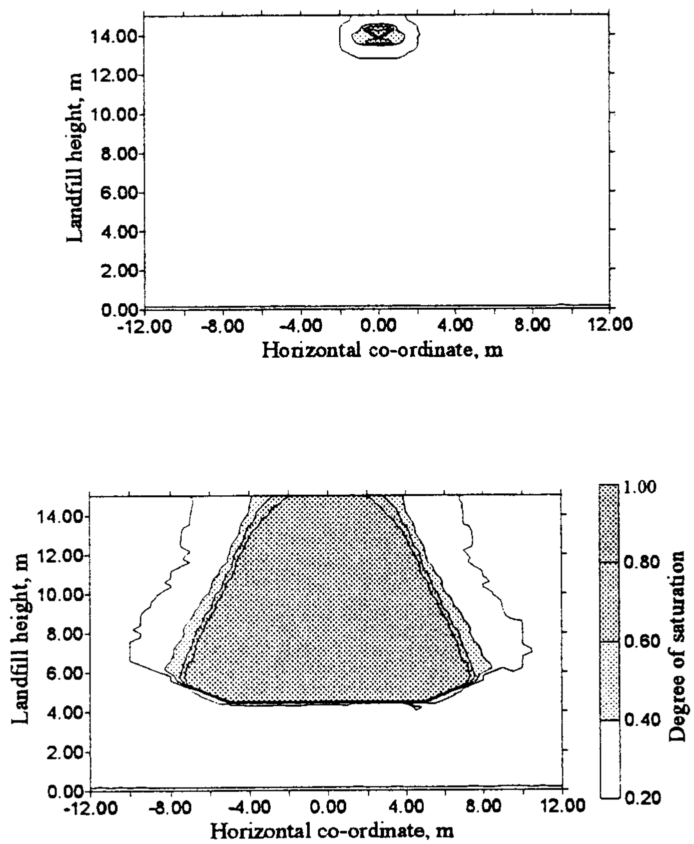
q_m	=	fluid flux at node 'm', MT^{-1}
q'	=	incremental flux unit, MT^{-1}
m	=	node number, unitless integer

For the case illustrated in Figure C-2, n is equal to 5 and then q' is equal to q/15, the uppermost node is numbered 1, the middle node is numbered 3 and the lowest node is number 5. The nodal fluxes are then:

$$q_1 = 1 \cdot q' = q/15,$$
$$q_3 = 3 \cdot q' = q/5, \text{ and}$$
$$q_5 = 5 \cdot q' = q/3.$$

Results

Degree of saturation iso-clines for the horizontal trench recirculating leachate at rates of 2.0 and 8.0 m^3/day/m of trench are depicted in Figures C-4a and C-4b respectively. Influence distance as a function of flow rate has been plotted in Figure C-5. The influence distance was defined as the lateral distance from the trench to which the saturation had been increased above the initial condition



(a) (b)

Figure C-4. Saturation profiles for horizontal trenches recirculating 2.0 and 8.0 m^3/day/m.

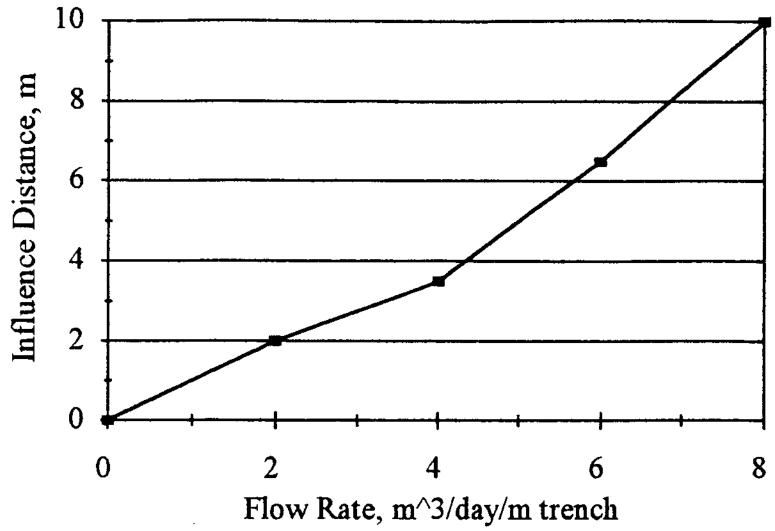
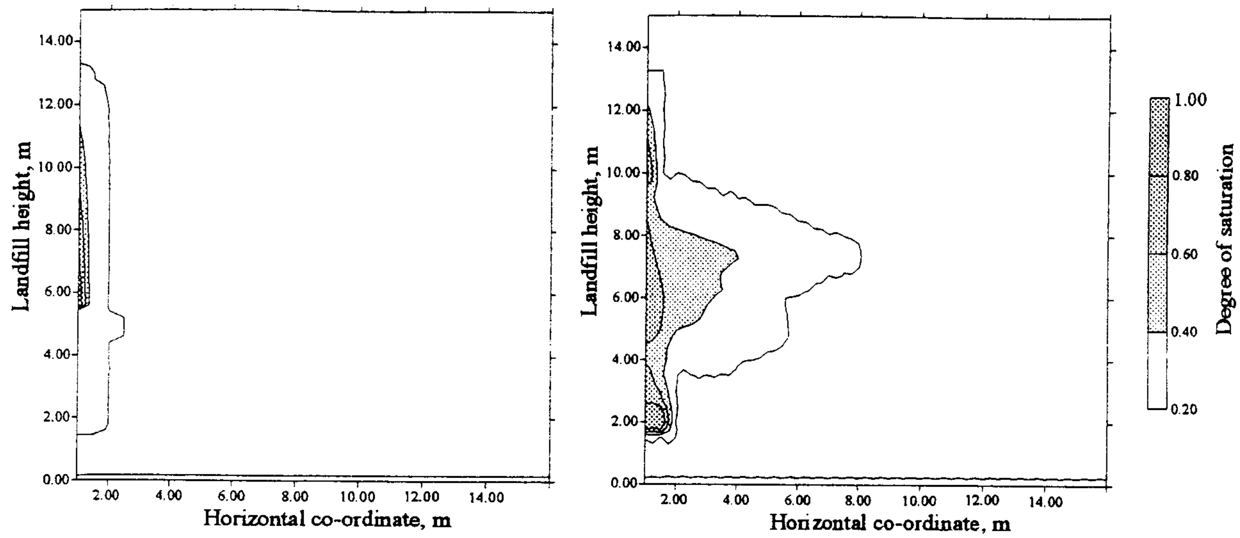


Figure C-5. Horizontal infiltration trench influence distance as a function of flow rate (single injection line results, transient conditions).

The degree of saturation iso-clines suggest that flow rates of 6.0 and 8.0 m^3/day/m trench result in the upward propagation of a saturated front and artesian conditions at the landfill surface. The influence distances in Figure C-5 should be used as guideline particularly when placing horizontal trenches near the landfill surface and boundaries. The influence distance may be doubled to determine trench spacing requirements.

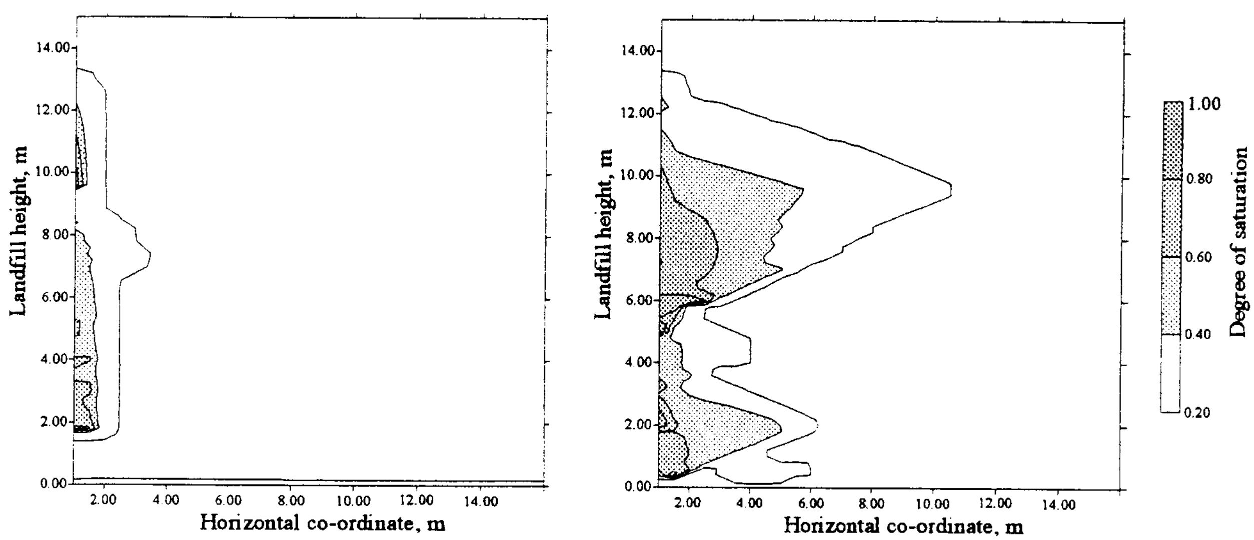
Two sets of simulations were conducted to assess the effect of trench spacing upon the degree of saturation profiles. The first set of simulations spaced the trenches at twice the influence distances noted in Figure C-5. In these simulations, a uniform wetting front developed approximately one meter beneath the injection level. In the second set of simulations, the trenches were spaced at 1 to 1.5 times the influence distances in Figure C-5. In these simulations, saturated conditions developed quickly above and below the injection level resulting in artesian conditions at the surface.

The vertical well was modeled at flow rates of 0.20, 0.40, and 0.80 m^3/day at a hydraulic conductivity of 10^{-3} cm/s for elapsed times of up to 44 days. The development of degree of saturation iso-clines for flow rates of 0.20 and 0.40 m^3/day are shown in Figures C-6 and C-7 respectively. It can be seen from Figures C-6 and C-7 that the leachate will initially show preferential flow along the well surface. Such flow may contribute to the localized subsidence around the wells at full-scale sites. Higher saturations (>0.6) will 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.



(a) (b)

Figure C-6. Saturation iso-clines at 22 days and 44 days, vertical well recirculating 0.20 m^3/day.



(a) (b)

Figure C-7. Saturation iso-clines at 22 days and 44 days, vertical well recirculating 0.40 m^3/day.

Summary and Conclusions

It must be recognized that the results presented herein are fairly idealized depiction of leachate recirculation operations. Leachate recirculation will be practiced on a periodic basis, waste is extremely heterogeneous, and waste characteristics change with time. However, this is the first attempt to model the routing of leachate through the waste using unsaturated conditions and provides important information for the design and operation of the leachate recirculating landfill.

The influence distances for both the trench and well are a direct function of the recirculation rate. The higher the recirculation rate, the greater the influence distance. However, increasing the recirculation rate may require injection under pressure and may result in leachate seeps, particularly in the case of the trench. The degree of saturation iso-clines for the horizontal trench suggest 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. Figure C-5 can be used as a guideline when installing horizontal trenches.

The vertical well was inefficient at wetting the upper portion of the landfill while the horizontal trench was 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.

References

Brown, K.W. and K.C. Donnelly (1988) "An Estimation of the Risk Associated with the Organic Constituents of Hazardous and Municipal Waste Landfill Leachates", Journal of Hazardous Wastes and Hazardous Materials, 5(1), 3.

Harper, S.R. (1995) "Design Elements Associated with leachate Recirculation at Existing, Unlined Landfills," Proceedings of the Seminar on Landfill Bioreactor Design and Operation Proceedings, Wilmington, DE, 45 - 64.

Harper, S.R. (August 2-5, 1993) "Design Elements Associated with Leachate Recirculation at New and Existing Landfills," presented at the SWANA's 31st Annual International Solid Waste Exposition, San Jose, California.

Korfiatis, G.P., et al. (1984) "Moisture Transport in a Solid Waste Column," J. of Env. Eng., 110(4), 780.

Lappala, E.G., et al. (1987), Documentation of Computer Program VS2D to Solve the Equations of Fluid Flow in Variably Saturated Porous Media, Water-Resources Investigations Report 83-4009, U.S. Geological Survey.

Miller, Lamar, et al. (1993) "Leachate Recycle and the Augmentation of Biological Decomposition at Municipal Solid Waste Landfills," presented at the FCSHWM First Annual Research Symposium, Orlando, Florida.

Pohland, F.D. (1995) "Landfill Bioreactors: Historical Perspective, Fundamental Principles, and New Horizons in Design and Operations," Proceedings of the Seminar on Landfill Bioreactor Design and Operation Proceedings, Wilmington, DE, 10 - 28.

Reinhard, M., *et al* (1984) "Occurrence and Distribution of Organic Chemicals in Two Landfill Leachate Plumes", Environmental Science and Technology, 18(2), 953.

Repa, E.W. (1988) "A Look at Superfund's' Municipal Landfills", Waste Age, 19(5), 86.

Sawney, B.L. and R.P. Kozloski (1984) "Organic Pollutants in Leachates from Landfill Sites", Journal of Environmental Quality, 13(3), 349.

Schultz, B. and P. Kjeldsen (1986) "Screening of Organic Matter in Leachate from Sanitary Landfills Using Gas Chromatography Combined with Mass Spectrometry", Water Research, 20(8), 965.

Voss, Clifford I. (1984), SUTRA, Saturated-Unsaturated Transport, A Finite-Element Simulation Model for Saturated-Unsaturated, Fluid-Density Dependent Ground-Water flow with Energy Transport or Chemically Reactive Single-Species Solute Transport, U.S. Geological Survey, national Center, Reston, Va.

Voss, Clifford I. (1991), SUTRA-SUTRA Plot - IGWMC - FOS 27 EXT, International Ground Water Modeling Center.

leachate recirculation parameters on leachate quality could be analyzed. Although COD was the main leachate quality parameter analyzed, the program can be used for any other leachate quality parameter as well which follows the same pattern of variation over time as COD. The following sections discuss the methodology utilized in detail.

MASS BALANCE APPROACH

Single Cell

For a single recirculating active cell, shown schematically in Figure D-1, a mass balance can be applied to arrive at equations which determine the leachate organic strength. The biological degradation of the organic portion of the waste mass is thought to be carried out by anaerobic microorganisms and proceed in three phases. The first phase called the hydrolysis phase, involves the transformation of higher-molecular compounds into compounds suitable for energy source. The second phase is called acidogenesis phase and is characterized by the formation of lower-molecular organic acids by a group of microorganisms called 'acidogens' or 'acid formers'. During these two phases of degradation of organic waste mass, the leachate organic concentration increases. During the third phase called the methanogenesis phase, the leachate organic strength decreases due to the conversion of organic compounds into end products, mainly methane and carbon dioxide. Methanogens are the microorganisms responsible for this conversion to end products. In actuality, as the active cell is filled, the older waste might have already advanced to the next phase of stabilization (methanogenesis) while fresh waste is still being placed in the same cell/section of the landfill. Thus, even in the same active cell, not all waste is in the hydrolysis/acidogenesis phases and the active cell can be visualized as two cells: one in the hydrolysis/acidification phase and the other in the methanogenesis phase. Figure D-1 is a schematic diagram illustrating this concept. Assuming that the cells behave as CSTRs, application of mass balance on the hydrolysis/acidogenesis portion of the cell yields:

$$V_a \frac{dC}{dt} = Q_a C_a + Q_p C_p - C'_a Q'_a + k_a C'_a V_a \qquad \text{(D-1)}$$

Where V_a = Void volume hydrolysis/acidogenesis portion of the cell

C = Leachate parameter concentration of the hydrolysis/acidogenesis portion of the cell

t = Time

Q_a = Flow into the cell

C_a = Concentration of the leachate parameter into the cell

Q_p = Moisture infiltration

C_p = Concentration of the infiltrating moisture

Q'_a = Flow out of the cell

C'_a = Concentration out of the cell

k_a = Reaction rate constant for the hydrolysis/acidogenesis portion of the cell

Since C_p is zero, between times (t) and (t+1), Equation D-1 can be written as:

$$V_a \frac{(C'_{a(t+1)} - C_{a(t)})}{\Delta t} = Q_{a(t)} C_{a(t)} - Q'_{a(t+1)} C'_{a(t+1)} + k_a C'_{a(t+1)} V_a \qquad \text{(D-2)}$$

Where C'a(t+1) and Ca(t) are the concentrations at times (t+1) and (t) respectively. Thus,

$$C'_{a(t+1)} = \frac{C_{a(t)} (Q_{a(t)} + V_a)}{(V_a + Q'_{a(t+1)} - k_a V_a)}$$

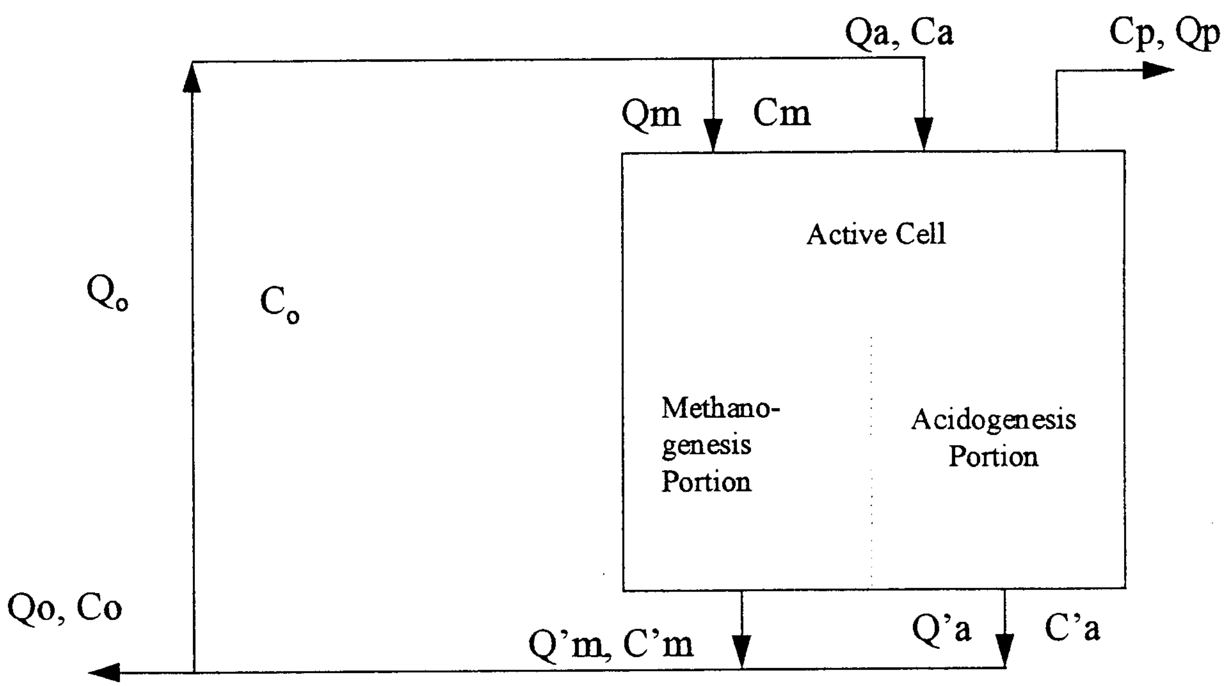


Figure E-1. Schematic Drawing of single recirculating active cell

Similarly, for the methanogenesis portion of the cell,

$$V_m \frac{dC}{dt} = Q_m C_m + Q_p C_p - Q'_m C'_m - k_m C'_m V_m \qquad \text{(D-4)}$$

Similarly, for the methanogenesis portion of the cell,

$$V_m \frac{dC}{dt} = Q_m C_m + Q_p C_p - Q'_m C'_m - k_m C'_m V_m \qquad \text{(D-5)}$$

Where
- V_m = Void volume in the methanogenesis portion
- C = Parameter concentration of the methanogenesis portion
- t = Time
- Q_m = Flow into the methanogenesis part
- C_m = Concentration into the methanogenesis part
- Q_p = Moisture infiltration
- C_p = Concentration of the infiltrating moisture
- Q'_m = Flow out of the methanogenesis part
- C'_m = Concentration out of the methanogenesis part
- k_m = Reaction rate constant of the methanogenesis part

The concentration of the infiltrating moisture is zero and thus Equation E-4 reduces to:

$$V_m \frac{dC}{dt} = Q_m C_m - Q'_m C'_m - k_m C'_m V_m \qquad \text{(D-5)}$$

Between times (t) and (t+1), Equation D-5 can be written as:

$$V_m \frac{(C'_{m(t+1)} - C_{m(t)})}{\Delta t} = Q_{m(t)} C_{m(t)} - Q'_{m(t+1)} C'_{m(t+1)} - k_m C'_{m(t+1)} V_m \qquad \text{(D-6)}$$

Where $C'_{m(t+1)}$ and $C_{m(t)}$ are the concentrations at times (t+1) and (t) respectively. Therefore,

$$C'_{m(t+1)} = \frac{C_{m(t)} (Q_{m(t)} + V_m)}{(V_m + Q'_{m(t+1)} + k_m V_i)} \qquad \text{(D-7)}$$

Equations D-3 and D-7 are used in the modified program to calculate the leachate parameter concentration over a time period using input parameters. The details are described in the following sections.

The equation used in the modified program to calculate the overall leachate parameter concentration is:

$$C_o = \frac{(C_m Q_m) + (C_a Q_a)}{(Q_m + Q_a)} \qquad \text{(D-8)}$$

where :
- C_o = Overall leachate parameter concentration
- C_m = Concentration out of methanogenesis portion of the active cell
- C_a = Concentration out of hydrolysis/acidogenesis portion of the active cell
- Q_m = Flow out of the methanogenesis portion of the active cell
- Q_a = Flow out of the hydrolysis/acidogenesis portion of the active cell

Two Cells

Considering two landfill cells, one closed and inactive and the other active (receiving wastes), and applying mass balance on each cell, equations can be developed to calculate the concentration of a leachate quality parameter. Although, in reality, landfill cells are neither Continuous Stirred Tank Reactors (CSTRs) nor plug flow reactors, because of the use of the apparent reaction rate constant, it is assumed that the cells behave as CSTRs. Also, because the inactive cell has been completely filled with waste and closed, it is assumed that there is no infiltration of moisture to that cell from sources other than recirculation. However, the active cell is open and receiving waste, therefore moisture infiltration resulting from precipitation occurs. A schematic diagram of the cells is shown in Figure D-2.

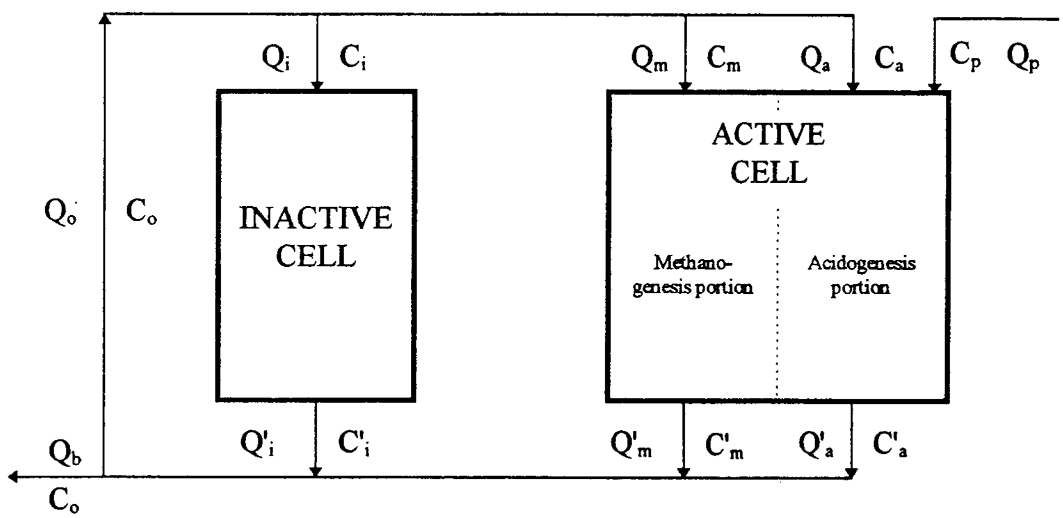


Figure D-2. Schematic diagram of two parts in the active cell

Applying mass balance to the inactive cell:

$$V_i \frac{dC}{dt} = Q_i C_i - Q'_i C'_i - k_i C'_i V_i \qquad \text{(D-9)}$$

Where: V_i = Void volume in the inactive cell

C	=	Parameter concentration of the inactive cell
t	=	Time
Q_i	=	Flow into the inactive cell
C_i	=	Concentration into the inactive cell
Q'_i	=	Flow out of the inactive cell
C'_i	=	Concentration out of the inactive cell
k_i	=	Reaction rate constant for the inactive cell

Since the cell is closed, there is no moisture infiltration into the inactive cell. Thus, flow into the inactive cell is equal to the flow out of the inactive cell. In other words, leachate flow out of the inactive cell is equal to the recirculation flow into the inactive cell. Also, since the cell is full, the volume V_i remains constant.

Over a time step, Equation D-9 can be approximated as:

$$V_i \frac{(C'_{i(t+1)} - C_{i(t)})}{\Delta t} = Q_{i(t)} C_{i(t)} - Q'_{i(t+1)} C'_{i(t+1)} - k_i C'_{i(t+1)} V_i \qquad \text{(D-10)}$$

Where $C'_{i(t+1)}$ = Concentration at time (t+1)
$C_{i(t)}$ = Concentration at time (t)
Δt = Time interval, assumed to be one day

Thus, concentration at time (t+1) reduces to:

$$C'_{i(t+1)} = \frac{C_{i(t)} (Q_{i(t)} + V_i)}{(V_i + Q'_{i(t+1)} + k_i V_i)} \qquad \text{(D-11)}$$

Similarly, applying mass balance to the methanogenesis portion of the active cell,

$$V_m \frac{dC}{dt} = Q_m C_m + Q_p C_p - Q'_m C'_m - k_m C'_m V_m \qquad \text{(D-12)}$$

Where V_m = Void volume in the methanogenesis portion
C = Parameter concentration of the methanogenesis portion
t = Time
Q_m = Flow into the methanogenesis part
C_m = Concentration into the methanogenesis part
Q_p = Moisture infiltration
C_p = Concentration of the infiltrating moisture
Q'_m = Flow out of the methanogenesis part
C'_m = Concentration out of the methanogenesis part
k_m = Reaction rate constant of the methanogenesis part

Since the active cell is subject to moisture infiltration, the terms Q_p and C_p are included in Equation D-12. Thus, the flow out of the portion of the landfill experiencing methanogenesis is greater than the recirculation flow by an amount equal to daily moisture infiltration. Initially, as the active cell fills, all the waste will be at the hydrolysis/acidogenesis phase, which implies that methanogenesis part will be absent. Only after the hydrolysis/acidogenesis portion of the active cells gets filled up completely, the methanogenesis portion starts filling. This implies that initially, the void volume of the methanogenesis portion of the active cell, V_m, remains zero until the hydrolysis/acidogenesis portion fills up. Then V_m starts increasing until the entire active cell fills. Eventually the entire cell reaches the methanogenic phase. The concentration of the infiltrating moisture is zero and thus Equation D-12 reduces to:

$$V_m \frac{dC}{dt} = Q_m C_m - Q'_m C'_m - k_m C'_m V_m \qquad \text{(D-13)}$$

Between times (t) and (t+1), Equation D-13 can be written as:

$$V_m \frac{(C'_{m(t+1)} - C_{m(t)})}{\Delta t} = Q_{m(t)} C_{m(t)} - Q'_{m(t+1)} C'_{m(t+1)} - k_m C'_{m(t+1)} V_m \qquad \text{(D-14)}$$

Where $C'_{m(t+1)}$ and $C_{m(t)}$ are the concentrations at times (t+1) and (t) respectively.

Therefore,

$$C'_{m(t+1)} = \frac{C_{m(t)} (Q_{m(t)} + V_m)}{(V_m + Q'_{m(t+1)} + k_m V_i)} \qquad \text{(D-15)}$$

Applying mass balance to the acidogenesis portion:

$$V_a \frac{dC}{dt} = Q_a C_a + Q_p C_p - Q'_a C'_a + k_a C'_a V_a \qquad \text{(D-16)}$$

Where
V_a = Void volume in the acidogenesis part
C = Parameter concentration of the hydrolysis/acidogenesis portion of the active cell
t = Time
Q_a = Flow into the acidognesis part
C_a = Concentration into the acidogensis part
Q_p = Moisture infiltration
C_p = Concentration of the infiltrating moisture
Q'_a = Flow out of the acidogenesis part
C'_a = Concentration out of the acidogenesis part
k_a = Decay rate constant for the acidogenesis part

Because the active cell is open, similar to the methanogenesis portion, moisture infiltration occurs in the hydrolysis/acidogenesis portion of the active cell. Thus, the flow out of the cell is greater than the recirculation flow into the cell. Since hydrolysis/acidogenesis acts to increase the leachate organic concentration, k has a positive value as opposed to negative value once methanogenesis starts. Initially, the hydrolysis/acidogenesis portion fills until the waste moves to the methanogenesis phase. From then on, the volume of the hydrolysis/acidogenesis part remains constant until the entire cell is filled. Thus, V_a initially increases and then remains constant until the entire cell is filled. Then V_a starts decreasing and eventually all the waste reaches the methanogenesis phase. Since C_p is zero, Equation D-16 reduces to:

$$V_a \frac{dC}{dt} = Q_a C_a - Q'_a C'_a + k_a C'_a V_a \qquad \text{(D-17)}$$

Between times (t) and (t+1), Equation D-17 can be written as:

$$V_a \frac{(C'_{a(t+1)} - C_{a(t)})}{\Delta t} = Q_{a(t)} C_{a(t)} - Q'_{a(t+1)} C'_{a(t+1)} + k_a C'_{a(t+1)} V_a \qquad \text{(D-18)}$$

Where C'a(t+1) and Ca(t) are the concentrations at times (t+1) and (t) respectively. Thus,

$$C'_{a(t+1)} = \frac{C_{a(t)} (Q_{a(t)} + V_a)}{(V_a + Q'_{a(t+1)} - k_a V_a)} \qquad \text{(D-19)}$$

Equations D-11, D-15 and D-19 are used in the program to calculate the leachate parameter concentration over a time period using input parameters. The details are described in the next section.

The equation used in the program to calculate the overall leachate parameter concentration is:

$$C_o = \frac{((C_i Q_i) + (C_m Q_m) + (C_a Q_a)}{(Q_i + Q_m + Q_a)} \qquad \text{(D-20)}$$

Where:
- C_o = Overall leachate parameter concentration
- C_i = Concentration out of inactive cell
- C_m = Concentration out of methanogenesis portion of the active cell
- C_a = Concentration out of hydrolysis/acidogenesis portion of the active cell
- Q_i = Flow out of the inactive cell
- Q_m = Flow out of the methanogenesis portion of the active cell
- Q_a = Flow out of the hydrolysis/acidogenesis portion of the active cell

PROGRAM INPUTS

Turbo C Version 2.01 was used to develop the program to iteratively calculate the leachate parameter concentration over a period of time. The program accepts a set of input parameters and calculates the leachate parameter concentration every day and upon successful completion, writes the concentration at the end of every month (30th day) onto a specified file in the same directory as the executable file. If no disk space is available the program will not write onto the file. If the specified file (an input to the program) already exists, the file will be overwritten.

Sample input screens are presented in the appendix. The program prompts for the input of the following parameters in the same order:

- length of the landfill cell in meters. This refers to the length of the cell or section of the landfill being analyzed.

- width of the landfill cell in meters. Together with the length, this determines the area receiving precipitation.
- depth of the landfill cell in meters. This refers to the average depth.
- density of the waste in Kg/m^3. This refers to the wet density of the waste as placed in the landfill cell. It is used with the waste placement rate to determine the volume of the waste being placed and in turn, determines when the cell gets completely filled.
- waste placement rate in Kg/day. The wet weight of waste being placed daily in the cell. This rate is assumed to be constant throughout the filling process.
- void volume of the waste as a percentage of the total volume which refers to the percentage volume of voids in the waste being placed. This, together with the saturation value, determines the actual volume available for leachate movement and reactions.
- moisture infiltration rate in m^3/day, the amount of moisture infiltrating the active cell which is determined by the product of average annual precipitation and the surface area of the active cell. It is assumed that this amount of moisture is added to the active cell every day.
- leachate bleeding rate as a percentage of the total leachate flow out of the two cells. This determines the amount of leachate going out of the system (wasted) and is calculated as a percentage of the total leachate flow from the two cells. It is assumed to be constant.
- time of inversion of 'k' in days, is the time required for the organic fraction of the waste to move from hydrolysis/acidogenesis phase (time at which the waste is placed) to the methanogenesis phase. This determines how long a batch of waste (daily cell) will be in the hydrolysis/acidogenesis phase (increasing the leachate organic strength) before changing to the methanogenesis phase (decreasing leachate organic strength).
- initial leachate concentration in mg/l is the leachate organic concentration in the leachate being recirculated for the first time. This is not zero because of the fact that the concentration of the leachate being recirculated for the first time will not be zero.
- initial leachate recirculation rate, in m^3/day, is the leachate recirculation rate at

the start of the process.

- positive k (day^{-1})value is the reaction rate constant for the hydrolysis/acidogenesis portion of the active cell.
- negative k (day^{-1}) value, the reaction rate constant for the methanogenesis portion of the active cell and the entire inactive cell.
- percent moisture saturation of the waste is the fraction of the void volume filled with moisture. This determines the leachate volume within the cell. This value, along with the void volume is used to determine the total reaction volume of the cells.
- name of the output file, the file containing the output upon successful completion of the program. If the disk is full, the file will not be created. If the specified file already exists, it will be overwritten.

ASSUMPTIONS MADE IN THE PROGRAM

Several assumptions are made within the program and are described in the following paragraphs. It is assumed that the landfill section is rectangular in geometry. The dimensions are used in the program to calculate the total volume of the cell or section and to determine when to stop filling the cell when it is completely filled. Also, it is assumed that the dimensions of the active cell (being filled and open) and inactive cell (filled and closed) are the same, i.e., their volume/capacities are the same.

It is assumed in the program that the hydrolysis/acidogenesis phase lasts for the number of days as specified by the time of inversion of k. This implies that the value of the reaction rate constant changes from a positive value to a negative value after a number of days equal to the time of inversion of k. Initially, the methanogenesis portion of the active cell is empty as the hydrolysis/acidogenesis portion is filling. After a time period equal to the time of inversion of k since placement, the waste shifts to methanogenesis and the volume of waste in the hydrolysis/acidogenesis portion declines until the hydrolysis/acidogenesis portion empties and all the waste in the cell will be in the methanogenesis phase.

The transition from hydrolysis/acidogenesis and methanogenesis is assumed to be sudden and not gradual. This implies that the k value suddenly reverses from positive to negative after a period equal to time of inversion.

The amount of cover material in both the active and inactive cells are assumed to take up ten percent of the total volume of each cell. The actual volume available for waste mass is ninety percent of the total volume of the cell. Also, settlement of waste mass over time is not taken into account in any of the cells and the volume of the waste mass is assumed to remain constant.

The hydraulic aspects of the leachate movement have not been considered in the program.

It is assumed that the flow of leachate through the waste mass in both the cells is smooth and unhindered. This implies that the leachate parameter concentration is the same at all points within the cells. The leachate from both the cells are mixed. A portion of the leachate is then wasted for external treatment and disposal. The quantity of leachate after bleeding is recirculated and distributed between the two cells proportional to the volume of waste in the two cells. The two conceptual cells of hydrolysis/acidogenesis and methanogenesis are assumed to be separated hydraulically and the leachates from these two portions are mixed only after exiting from the cells. The scheme of leachate recirculation is assumed to be as shown in Figure D-2. The wasting rate is assumed to be the total flow from the active and inactive cells minus the flow into the active and inactive cells.

The amount of moisture infiltration is based on the average daily precipitation falling within the active area of the landfill. This parameter is a user input. This amount is added to the active cell every day (every iteration in the program). The amount of infiltrating moisture is assumed to be distributed between the methanogenesis and hydrolysis/acidogenesis parts of the active cell in proportion to the volume of the waste in the respective parts.

The details about the working of the program are described in the next section. Initially, as the active cell is filled, there is no waste in the methanogenesis portion of the active cell. As the cell fills, oldest waste moves from the hydrolysis/acidogenesis phase to the methanogenesis phase. From this point on, the methanogenesis portion grows as the active cell fills and the active volume (in the hydrolysis/acidogenesis phase) remains constant for a period (until the entire active cell fills) and then begins to decline. Once there is no more input to the active cell, the waste in the hydrolysis/acidogenesis phase shifts to the methanogenesis phase. In an actual landfill, as one cell fills, the next section is opened and so on, until the entire landfill area is completed.

PROGRAM EXECUTION

The program execution is started by typing the program name "Recirc", which is an executable file, at the DOS prompt. The program begins and clears the screen and displays a brief message. Upon pressing any key, it clears the screen and displays an input screen. The return/enter key has to be pressed after typing in each input parameter. After the first input screen, the second input screen is displayed. After accepting all the inputs, the program starts execution. The output is displayed on the screen. Then the output is written onto the specified file in the same directory in which the executable program resides. The output file is not created if there is no disk space or if the specified file already exists. After successful completion of the program and creating the specified output file, the program prompts for another run of the program.

Since the range of values for each of the input parameter is very wide, no validation of the input parameters is performed within the program. Also, since it is used to analyze the effect of various parameters on leachate quality parameter, restricting the range for input parameter is not desirable.

The first step of the program is to determine the void volume in the inactive cell based on the input dimensions of the cell. The inactive cell is "created" and assumed to have the same dimensions as that of the active cell. The void volume of the daily cell is also determined. Then the initial flow rate with initial leachate parameter concentration is assumed to flow into the cells after the waste is "placed" in the hydrolysis/acidogenesis portion of the active cell. Initially, as the hydrolysis/acidogenesis portion fills, the methanogenesis portion of the active cell is empty. Thus, there is no flow into the methanogenesis portion of the active cell when there is no waste present. Also, since the flow from the both active and inactive cells is mixed, as shown in Figure D-2, the input concentration into both the cells will be the same.

The time at which the first batch of waste (daily cell) is placed in the active cell is considered to be day one. All further time references are with respect to this point. There is a counter in the program to keep track of time so that the program knows when to shift the waste from the hydrolysis/acidogenesis phase to the methanogenesis phase based on the time of inversion of k.

All the calculations are performed on a daily basis and the concentration of the leachate constituent parameter is recorded once every thirty days. At every increment of time (a day), the program performs the following calculations and routines:

- If the active cell is not completely full, waste is placed in the hydrolysis/acidogenesis portion of the active cell. The waste capacity of the active cell is determined by the dimensions (volume) of the active cell. If the time elapsed since placing the first daily cell is more than time of inversion of k, then the waste is shifted to the methanogenesis phase. The shifted quantity of waste is equal to the daily placement rate (daily cell). From this point on until the active cell fills, the hydrolysis/acidogenesis portion can be visualized to have the same volume of waste. However, this may not be the case if the waste placement rate is very high where the active cell fills within a time period of time of inversion of k.
- If the active cell is full and more than the time of inversion has passed, then the waste from the hydrolysis/acidogenesis phase is shifted to methanogenesis. This means that the hydrolysis/acidogenesis volume starts decreasing and eventually reaches zero while all the waste shifts to methanogenesis phase. The hydrolysis/acidogenesis portion of the active cell ceases to exist once the volume in this portion reaches zero.
- The leachate flow into the cells are calculated based on the input parameters. Since the inactive cell is closed, it is assumed that there is no moisture infiltration and the leachate flow out of the inactive cell is the same as the inflow. However, since the active cell is open and moisture infiltrates, the flow out of the active cell is greater than the recirculation flow into the cell. The flow out of the active cell is greater than the inflow by an amount equal to the average daily infiltration. It is assumed that the average daily infiltration is distributed between the hydrolysis/acidogenesis and the methanogenesis portions proportional to their respective waste volumes. The

hydrolysis/acidogenesis and methanogenesis portions of the active cell are assumed to be hydraulically separated.

- The concentrations of the leachate quality parameter is calculated next. First the output concentration of the inactive cell is calculated using Equation D-11. The output concentration of the methanogenesis portion of the active cell is calculated using the Equation D-16 and that of hydrolysis/acidogenesis portion using Equation D-19. Once the output concentrations are calculated, the flows are mixed before wasting. The new average concentration is calculated using Equation D-20, which becomes the input concentration for the cells for the next time step. Depending on the input, a certain amount of leachate is bled out of the system. The remaining quantity is recirculated into the cells and is distributed between the active and inactive cells proportionally to the amount of waste present in each cell. The quantity of leachate flowing into the active cell is again in turn distributed between the hydrolysis/acidogenesis part and methanogenesis part proportionally to the volume of wastes in the respective parts. There will be no recirculation flow into the any part of the cell which is empty. Thus, there will be no flow into the methanogenesis portion initially and there will be no flow into the hydrolysis/acidogenesis portion towards the end.
- The above procedure is repeated thirty times (thirty days). The output concentrations from the inactive cell, the hydrolysis/acidogenesis and methanogenesis portions of the active cell are stored in a table within the program. Then the program continues for another thirty days before storing the output concentrations again. This procedure is repeated until the concentrations are recorded (within the internal memory and not on the disk)for a specified time period of approximately twenty years. The concentrations are not written to the file directly because it is more efficient to store the values of concentrations internally within the program and write on to the file once all the concentrations are calculated and stored. The program checks for disk space before creating the output file. If there is no sufficient disk space or if the disk is write protected, the output file is not created. The output format of the program is detailed in the following section.
- After the successful completion of one run of the program for a certain set of input parameters, the program prompts for another run. If the user enters 'y' (for yes), then the program starts all over again from the message screen. The process is repeated until the user enters 'n' when the program prompts for another run. If the user enters 'n' (for no), the program terminates normally and returns to the DOS prompt.