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.