SOLID WASTE MANAGEMENT: NEW TRENDS IN LANDFILL DESIGN

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To move into the twenty-first century in solid waste management and deal with the increasing fraction of solid waste going to landfills, the various regulatory agencies must try to develop a new strategy to optimize the use of existing landfills and prolong the life of any new ones. In the past 10 years, solid waste diversion technologies have only succeeded in diverting about 35% of the total solid waste stream. One promising approach is through the mass processing of municipal solid waste in "bioreactor" landfills. In a bioreactor landfill environment, the solid waste actively decomposes rather than being simply buried in a "dry tomb". This active decomposition is possible because over half the MSW waste stream is comprised of organic material (food, paper, etc.), which will decompose fairly rapidly under the right conditions. Under this model landfills become processing facilities. This model represents a dramatic shift from the dry tomb model currently designed in various parts of the world. Rather than being kept dry, the solid waste is actively moistened by injecting leachate into the landfilled solid waste to accelerate decomposition. Additionally, air may be actively introduced into the solid waste to further hasten decomposition by establishing aerobic conditions, replacing the anaerobic conditions that prevail in a conventional landfill.

1. INTRODUCTION

The generation of solid waste has become an increasingly important global issue over the last decade due to the escalating growth in world population and large increase in waste production. This increase in solid waste generation poses numerous questions concerning the adequacy of conventional waste management systems and their environmental effects. Landfill disposal is the most commonly used waste management method worldwide (Figure 1), and new methods are required to reduce GHG emissions from landfills. Landfills have served as ultimate receptors for municipal refuse, industrial residues, recyclable discards and wastewate sludge.

Engineered bioreactor landfills are usually designed to minimize the infiltration of rainwater and/or snowmelt into the solid waste. The design objectives of these landfills are to minimize leachate migration into the subsurface environment and maximize landfill gas generation rates under controlled conditions. Under the past ten years, experimental testing and field pilot studies have been conducted to develop and improve landfill techniques and designs, the goal being to control the negative effects of landfill sites on the environment (Warith et al 1999; Barlaz et al. 1990). There are many advantages to enhancing solid waste degradation such as reducing the time period of leachate treatment, increasing methane production, accelerating the subsidence of waste, thus permitting...
Figure 1. Trends in waste generation, recovery and disposal (Source: USEPA1996).

Figure 2. Components of integrated municipal solid waste management system.
landfill air space recovery and the reduction of contamination life span (Al-Youssifi and Pohland 1993). Techniques used to enhance biological degradation are: shredding the waste, leachate recirculation and addition of nutrients and sludge. Other techniques include controlling features, such as temperature and moisture content (Warith 2002), also proved to be pertinent in accelerating municipal solid waste (MSW) biodegradation.

Engineered bioreactor landfill sites can provide a more controlled means by which society can reduce the emission of global warming landfill gas (LFG), additionally they can provide immediate improvements to the surrounding local environment (Pohland, 1995). This landfill technology is gaining popularity and has been tried both in pilot and full scale in various landfills in North America, particularly in areas where landfill closure is costly and/or where landfill space is crucial. Engineered bioreactor landfills provide accelerated waste biodegradation, a means for recovery of capacity or air space and a means to enhance LFG generation rates (McCreanor and Reinhart 1996).

Landfill continues to be the major disposal route for municipal solid waste. Wastes in landfill experience physical and biological changes resulting in solubilization or suspension of high concentrations of organic matter in the landfill’s leachate. Source reduction and waste minimization, resource recovery and recycling, waste processing and treatment, combustion and land filling have all significantly affected the sufficiency of waste management systems. Of all available management options for solid waste management, landfill disposal is the most commonly employed waste management worldwide. Such landfill have served as ultimate waste receptors for municipal refuse, industrial or agricultural residues, wastewater sludge, incinerator ash, recycle discards, and/or treated hazardous wastes, and have thereby promoted greater interest in landfill system innovation and advancement. Figure 2 shows the difference between the conventional landfill and bioreactor landfill in terms of the completion of waste decomposition process. As shown in the figure, the volume of bioreactor is smaller than the conventional landfill even after 10 years.

In a conventional (dry) landfill, the wastes are delivered to the landfill, spread out, compacted and covered at the end of the day with a thin layer of soil, until a planned depth is reached, then the waste is covered with clay as a final layer. The problem with conventional-dry landfills is that it takes several decades (30-200 years) for the waste to fully decompose. Also, liner failure could happen in conventional-dry landfill sometime in future, which can cause serious groundwater contamination (Rosenberg, 2000).

2.1 BIOREACTOR MECHANISM

Bioreactor landfill is an emerging technology for solid waste management. The basic concept of bioreactor landfill is to use specific design and operation practices to accelerate the decomposition of food waste, green-waste, paper and other organic wastes in a landfill by promoting optimum moisture content and sufficient nutrients for the microorganisms to degrade the waste. The method not only enhances the degradation processes, but also stabilizes the landfill as quickly as possible. Landfill stabilization means that the environmental performance parameters (landfill gas composition, generation rate and leachate concentration) remain at a steady level. Biological processes are known to reduce the fraction of solid waste. Leachate recirculation system in a bioreactor landfill is one of the techniques that can be used to enhance solid waste biodegradation. Landfill's leachate may contain high concentration of organic and inorganic materials including toxic compounds and heavy metals (Craven et al, 1999). The recirculation of landfill's leachate accelerates the rate at which the waste is broken down, thus decreasing the time required to stabilize the landfill's site.
This is important because the longer a landfill remains un-stabilized, the longer it remains as a source for potential environmental problems (e.g., groundwater contamination and methane gas migration). Bioreactor landfill avoids the problem of future liner failure because the wastes decompose within (5-10) years.

2.2 BIOREACTOR LANDFILL TYPES

Aerobic-Anaerobic:
The aerobic-anaerobic bioreactor is designed to accelerate waste degradation by combining attributes of the aerobic and anaerobic bioreactors. The objective is to cause a rapid biodegradation of food and other easily degradable waste in the aerobic stage to reduce organic acids in the anaerobic stage resulting in the earlier methanogenesis. In this system, the uppermost lift of waste is aerated while the lifts below receive liquids. Horizontal wells, installed in each lift during construction, are used to transport landfill gases, liquids and air.

Anaerobic:
The anaerobic bioreactor (Figure 4) seeks to accelerate the degradation of waste by optimizing conditions for anaerobic bacteria. Anaerobic bacteria are responsible for converting organic wastes into organic acids and ultimately into methane and carbon dioxide. The moisture condition that is required to optimize anaerobic degradation is about field capacity or (35-40)% moisture. The moisture content in typical landfills is around (10-20)% water. Moisture is typically added in a form of leachate through a variety of delivery systems. Sewage sludge can be added too as a source of moisture. This leads to an increase in the amount of landfill gas production that is then collected by the gas collection system in the landfill.

Aerobic:
The Aerobic Bioreactor (Figure 5) accelerates waste degradation by optimizing conditions for aerobes that are organisms that require oxygen for cellular respiration. In aerobic respiration, energy is delivered from organic molecules in a process that consumes oxygen and produces carbon dioxide. Aerobes require sufficient water to function as anaerobes. Aerobic organisms can grow more quickly than anaerobes because aerobic respiration is more efficient at generating energy than anaerobic respiration. In landfills, aerobic activity is promoted through injection of air into the waste mass. The aerobic process does not generate methane. The aerobic process is very accelerated and typically requires less than two years for full biodegradation.

Facultative Bioreactor:
The facultative bioreactor combines conventional anaerobic degradation with a mechanism for controlling the high ammonia concentration that may be developed when liquids are added to the landfill (Figure 6). In this system, leachate containing high levels of ammonia is treated using the biological process of nitrification. The nitrifying bacteria convert the ammonia to nitrate that can be used by facultative bacteria in the absence of oxygen for respiration. A Facultative bioreactor requires adequate moisture to function optimally. Leachate and other liquids (biosolids, surface water, etc) are used to increase the moisture content of the waste.

2.3 GENERATION OF LANDFILL GASES

The concept of bioreactor landfill considers water and solid waste, as major inputs while leachate and gas are the principal outputs. The primary gases that can be found in landfills include ammonia, carbon dioxide, methane, nitrogen and oxygen. They are produced from the decomposition of the organic fraction of municipal solid waste. Methane and carbon dioxide are considered the main landfill gases that are produced from biodegradable organic waste components in landfill. The generation of landfill gases can be divided into five-phases:

- **Initial Adjustment Stage**: The organic biodegradable components in municipal solid waste undergo a microbial decomposition with the presence of oxygen soon after the waste is placed in the landfill. In this phase, biological composition occurs under aerobic reaction in which oxygen is consumed by aerobic microorganisms. Digested wastewater treatment plant sludge and recycled leachate can be considered as other sources of organisms. The aerobic decomposition generates heat, and temperature (10-20°C) higher than the refuse placement temperature (Rovers et al, 1995).
Figure 4. Anaerobic Bioreactor Landfill (Source: Waste Management, 2000).

Figure 5. Anaerobic Bioreactor Landfill (Source: Waste Management, 2000).

Figure 6. Facultative Bioreactor Landfill (Source: Waste Management, 2000).
Transition Phase: In this phase, oxygen is exhausted and the anaerobic conditions begin to develop. Nitrate and sulfate, which serve as electron acceptors, are converted to nitrogen gas and hydrogen sulfide during biological conversion reactions. The onset of anaerobic conditions can be observed by measuring the oxidation/reduction potential of the waste. The generation of methane occurs when the oxidation/reduction potential values are in the range of 150 to 300 millivolts (Rovers et al, 1995). During the transition phase, the pH of the generated leachate starts to drop due to the high concentrations of carbon dioxide and the presence of organic acids.

Acid Phase: Microbial activates which are originally initiated in second phase, accelerate significant amount of organic acid and reduce the hydrogen gas. There are two major reactions that occur in this phase. The first reaction is the enzyme-mediated transformation (hydrolysis) of higher molecular mass components (e.g., lipids, polysaccharides, proteins, and nucleic acids) into compounds that can be used by microorganisms as sources of energy. Acidogenesis is the second reaction of this phase, which involves the conversion of microbial compounds resulting from the first reaction into lower molecular mass, compounds such acetic acid (CH₃COOH). The microorganisms involved in this conversion are often known as non-methanogenic or acidogens (Rovers et al, 1995). Carbon dioxide is the primary gas generated during this phase with a small amount of hydrogen gas. The pH of generated leachate drops to 5 or lower due to the elevated concentration of CO2 inside the landfill. The biochemical oxygen demand (BOD₅), chemical oxygen demand (COD) and conductivity of the leachate will increase due to the dissolution of the organic acids in the leachate. Many inorganic constituents in particular heavy metals will be solubilized during this phase due to the low pH value of landfill’s leachate.

Methane Fermentation Phase: A group of microorganisms convert the acetic acids and hydrogen gas to methane and carbon dioxide. The microbes responsible for this reaction are called methanogenic or methanogens. The pH values, due to methanogenic reaction, will rise to more natural values in the range of (6.8-8). The BOD₅ and COD values of the landfill’s leachate will be reduced. Also, the concentration of heavy metals in the landfill’s leachate will drop.

Maturation Phase: This phase starts after the biodegradable organic material is converted to methane and carbon dioxide. The rate of landfill gas generation is reduced significantly in this phase as most of the available nutrients are removed with leachate during the methanogenic phase and the remaining substrates are slowly biodegradable. CO₂ and CH₄ are the primary landfill gases in this phase. Small amounts of nitrogen may be also found in the landfill gas. During maturation phase, leachate will contain humic and fulvic acids which are difficult to process biologically. The production of CH₄ declines as waste organics get depleted. However, the slowly biodegradable organics generate methane for decades (e.g., cellulosic organics such as wood and paper).

2.4 SOLID WASTE DECOMPOSITION PROCESS

Decomposition of refuse in a landfill occurs through a complex series of microbial reactions. Initial aerobic decomposition occurs producing mainly carbon dioxide and water vapor. Anaerobic decomposition begins somewhere between 2 months and 2 years after waste is placed in the landfill. Hydrolytic and fermentative microorganisms convert complex organic materials (such as food and garden waste, and paper products), to intermediate carboxylic acids, particularly acetic acid, alcohols, hydrogen, and carbon dioxide. Acetogenic bacteria produce acetate, hydrogen, and carbon dioxide from longer-chain carboxylic acids and alcohols. The end reaction is the production by methanogenic to bacteria of methane (Hudgins, 1999).

3. LANDFILL LEACHATE

Leachate is a liquid that has percolated through solid waste and has extracted, dissolved, and suspended materials that may include potentially harmful materials. The type of solid waste, physical, chemical, and biological activities that occur in the solid waste determines the quality of leachate. The quantity of leachate seeping from the landfill is proportional to the build up of leachate within the landfill, alternatively called leachate mound. Leachate can cause serious problems since it able to transport contaminating materials that may cause a contamination of soil, groundwater and surface water.

3.1 LEACHATE MANAGEMENT SYSTEMS

The management of leachate is the key to eliminating potential landfill problems. A number of specific practices have been used to manage the leachate collected from landfill sites. These techniques include:

3.2 LEACHATE RECIRCULATION

An effective method for the treatment of the leachate is to collect and recirculate the leachate through the
landfill. During the early stages of landfill operations, the leachate will contain significant amounts of TDS, BOD, COD, and heavy metals. When leachate is recirculated, biological, physical and chemical reactions will occur and provide treatment for BOD. The recirculation of leachate provides the landfill with various nutrients, which are required for the growth of bacteria that participate in anaerobic degradation of the waste. Leachate recirculation will increase a landfill’s moisture content. Moisture is essential for the activities of all microorganisms because it serves as a medium for transporting nutrients and bacteria. During leachate recirculation, the leachate is returned to a lined landfill for reinfiltration into the municipal solid waste. This is considered a method of leachate control because as the leachate continues to flow through the landfill it is treated through biological processes, precipitation, and sorption. This process also benefits the landfill by increasing the moisture content, which in turn increases the rate of biological degradation in the landfill, the biological stability of the landfill, and the rate of methane recovery from the landfill (Warith 2002).

3.3 LEACHATE EVAPORATION

One of the simplest techniques that can be used as a leachate management system is leachate evaporation. It involves the use of lined leachate evaporation ponds. Leachate that is not evaporated is sprayed on the completed portions of the landfill. In some locations with high rainfall, the lined leachate storage facility is covered with geomembrane during the winter season to exclude rainfall. Odorous gases that may accumulate under the surface cover are vented to a compost or soil filter.

3.4 LEACHATE TREATMENT

A number of options have been used for the treatment of leachate. The treatment process selected will depend on the contaminants to be removed. The principal biological, physical and chemical treatments options used for the treatment of leachate include:

- Activated sludge, responsible for the removal of organics
- Nitrifications, responsible for the removal of nitrogen
- Neutralization, responsible for pH control
- Precipitations, responsible for the removal of metals and some anions
- Ion exchange, responsible for the removal of dissolved inorganics

3.5 LEACHATE CHARACTERISTICS

**Young Leachate:** Landfill’s leachate contains a biodegradable organic matter for the first few years (Mcbean et al, 1995). Therefore, this young leachate tends to be acidic due to the presence of volatile fatty acids. The pH is generally in the range of 6 to 7 and may be lower in a dry-stressed landfills. The young leachate is derived from processes such as the complex biodegradation of organics (e.g., cellulose) and simple dissolved organics (e.g., organic acids). Gradually, leachate becomes less strong and simply dissolved organics (e.g., gases CH4, CO2, H2, H2O and biomass).

**Old Leachate:** The pH of landfill’s leachate will increase to the range of 7 to 8 due to the depletion of the biodegradable organics and the production of gases. The changes occur after 4 to 5 years of waste deposited in the landfill. The Nitrogen level will indicate the age of the leachate. Ammonia nitrogen (NH3-N) and organic nitrogen (Org-N) are produced by the decomposition of organic and are stable in the anaerobic environment. Nitrate nitrogen (NO3-N) will be consumed during the anaerobic reaction.

3.6 METHODS OF LEACHATE RECIRCULATION

Leachate recirculation is one of the emerging techniques that can be used to manage leachate from landfill. Leachate should always be controlled, treated, or contained before it is released to the environment. During leachate recirculation, the leachate is returned to a lined landfill for reinfiltration into the municipal solid waste.

This is considered a method of leachate control because as the leachate continues to flow through the landfill, it is treated through biological processes, precipitations and sorption (Warith et al. 1999). This process also benefits the landfill by increasing the moisture content which in turn increases the rate of biological degradation in the landfill, the biological stability of the landfill, and the rate of methane recovery from the landfill. There are several methods of leachate recirculation. These include:

- Direct application to the waste during disposal. In this process, the leachate is added to the incoming solid waste while its being unloaded, deposited, and compacted. The problems with this method include odor problems, health risks due to exposure, and off-site migration due to drift. This method also requires a leachate storage facility for periods such as high winds, rainfall, and landfill shutdown when the leachate cannot be applied.

- Spray Irrigation of landfill surface. The leachate is applied to the landfill surface in the same method that irrigation water is applied to the crops. This method is beneficial because it allows the leachate to be applied to a larger portion of the landfill. Also, the leachate volume is reduced due to evaporation. However, the disadvantages...
associated with direct application are associated with this method as well.

- **Surface application.** This is achieved through ponding or spreading the leachate. The ponds are generally formed in landfill areas that have been isolated with soil berms or within excavated sites in the solid wastes. The disadvantages associate with this method include an increase in the amount of required land area, monitoring of the ponds to detect seepage, leaks, and breaks that would make it possible for the leachate to escape directly or with storm water runoff.

- **Subsurface application.** This method achieved throughout placing either vertical recharge wells or horizontal drains fields within the solid waste. There is a large amount of excavation and construction required with this method, but the risk of atmosphere exposure is radically reduced.

- **Another method of leachate management is to pump out the leachate from the bottom of the landfill and store it in a large basin.** The leachate is often shipped to a municipal wastewater treatment facility where it can be effectively treated. Since the concentration of leachate’s contamination is not high as that of commercial wastewater, the leachate serves as a dilutor and is consequently helpful.

### 3.7 ADVANTAGES AND DISADVANTAGES OF LEACHATE RECIRCULATION

**The advantages of leachate recirculation are:**

- **Leachate recirculation increases the rate at which the waste decomposes and this increases the rate of methane production.**

- **Leachate recirculation is a leachate management method that is relatively simple and inexpensive.**

**The disadvantages of leachate recirculation are:**

- Since landfills are heterogeneous, the leachate may find discrete channels to travel through. This makes it difficult to insure that the leachate is reacting with all of the waste and is thoroughly treated.

- The risk of environmental exposure when leachate is applied to the surface of a landfill.

### 3.8 FACTORS AFFECTING THE GENERATION OF LANDFILL GAS

There are several factors influence the rate of landfill gas generation. Theses parameters include moisture content, nutrient content, pH level, bacterial content, oxygen concentration, and temperature. These factors alone may not be critical, however, they may influence other parameters that control municipal solid waste degradation rates and activities (Pohland 1995).

- **Moisture Content:** This is considered the most important parameter in solid waste decomposition and gas production. It provides the aqueous environment necessary for gas production and also serves as a medium for transporting nutrients and bacteria throughout the landfill. Landfill gas is produced at all landfills because the substance moisture level required by methanogenic bacteria is very low and occurs even in dry landfill. Gas production is increased as moisture content is increased up to field capacity because nutrients, alkalinity, pH, and bacteria are not transferred readily within the landfill. If the moisture content in the waste exceeds the field capacity, the moving liquid will carry nutrients and bacteria to other areas within the landfill, creating an environment favorable to increase gas production. The overall moisture content of landfill’s refuse ranges typically from 15 to 40 percent. The moisture movement in landfill decomposing waste increases gas production by 25 to 50 percent over the production observed during minimal moisture movement.

- **Nutrient Content:** Microorganisms that participate in anaerobic degradation of solid waste require various nutrients for their growth. These nutrients include carbon, hydrogen, oxygen, nitrogen, phosphorus, sodium, potassium, calcium, magnesium and other trace materials. These nutrients are found in most landfills. However, inadequate homogenization...
of the waste may result in a nutrient limited environment. Toxic materials such as heavy metals can slow the bacterial growth and consequently retard gas production. The greater the amount of digested nutrients, the greater rate of gas generation.

- **pH Level**: The pH of the refuse and leachate significantly influences the chemical and biological processes. An acidic pH increases the solubility of many constituents, decreases adsorption, and increase the ion exchange between the leachate and organic matter. The optimum pH range for anaerobic reaction is 6.7 to 7.5. Within the optimum pH range, methanogens grow at high rate leading to maximum methane production. The rate of methane production is seriously limited when the pH level is lower than 6 or higher than 8 (Barlaz et al, 1987). The presence of industrial wastes, alkalinity and groundwater infiltration may affect the pH level in a landfill. During the initial stages of anaerobic decomposition, organic acids forms and result in an acidic pH. As these organics begin originate, the pH should rise as the acids are converted to methane.

- **Bacterial Content**: The bacteria involved in aerobic biodegradation and methanogenesis exist in the soil and refuse. However, the addition of bacteria from other sources to the refuse can result in a faster rate of development of the bacteria population. Digested effluent and wastewater sludge can be the sources of additional bacteria.

- **Oxygen Content**: Methanogenic bacteria are particularly sensitive to the presence of oxygen. Extensive gas recovery pumping may create a substantial vacuum in the landfill, forcing air in. This will extend the aerobic zone in the landfill refuse and eventually prevent the formation of methane in these layers (Christensen et al. 1989). Aerobic bacteria in the top of the landfill, under normal condition, will cause solid waste to readily consume the oxygen and limit the aerobic zone of the compacted waste.

- **Temperature**: The rate of methane generation can be increased, up to 100 times, when the temperature raises from 20 to 40 °C (Christensen et al, 1989). Moreover, in a deep landfill with a moderate water flux, landfill temperature of 30 to 45 °C can be expected for more temperature climates. The heat is a result of anaerobic decomposition process that can result in a temperature rise within the landfill environment. The heat flux from the landfill to the surroundings can also be resulted from the insulating effect of the solid waste.

4. **SUMMARY**

A bioreactor landfill is a sanitary landfill site that uses enhanced microbiological processes to transform and stabilize the readily and moderately decomposable organic waste constituents within 5 to 8 years of bioreactor process implementation. The bioreactor landfill significantly increases the extent of organic waste decomposition, conversion rates and process effectiveness over those that otherwise occur within the traditional landfill sites. Stabilization means that the environmental performance measurement parameters (LFG composition and generation rate, and leachate constituent concentrations) remain at steady levels, and should not increase in the event of any partial containment system failures beyond the lifetime of the bioreactor.

A bioreactor landfill site requires specific management activities and operational modifications to enhance and accelerate microbial decomposition processes. The single most important aspect for effective operation is liquid addition and management. Other strategies, including waste shredding, pH adjustment, nutrient addition and balance, waste pre-disposal and post-disposal conditioning, and temperature management, may also serve to optimize the bioreactor process. The successful operation of bioreactor landfill also requires the development and implementation of focused operational and development plans to ensure that optimal conditions for bioprocesses exist and to allow the system to function effectively.

**Advantages of Bioreactor Landfill can be summarized as follows:**

- Enhance the LFG Generation Rates
- Reduce Environmental Impact
- Production of End Product that does not Need Land filling
- Overall Reduction of Land filling Cost
- Reduction of leachate Treatment Capital and Operation Cost
- Reduction in Post-Closure care, maintenance and
- Overall reduction of contaminating life span of the landfill due to a decrease in contaminant concentrations during the operating period of the bioreactor landfills

5. **REFERENCES**


