Bioreactor/Bio-Stabilization Technologies

Overview

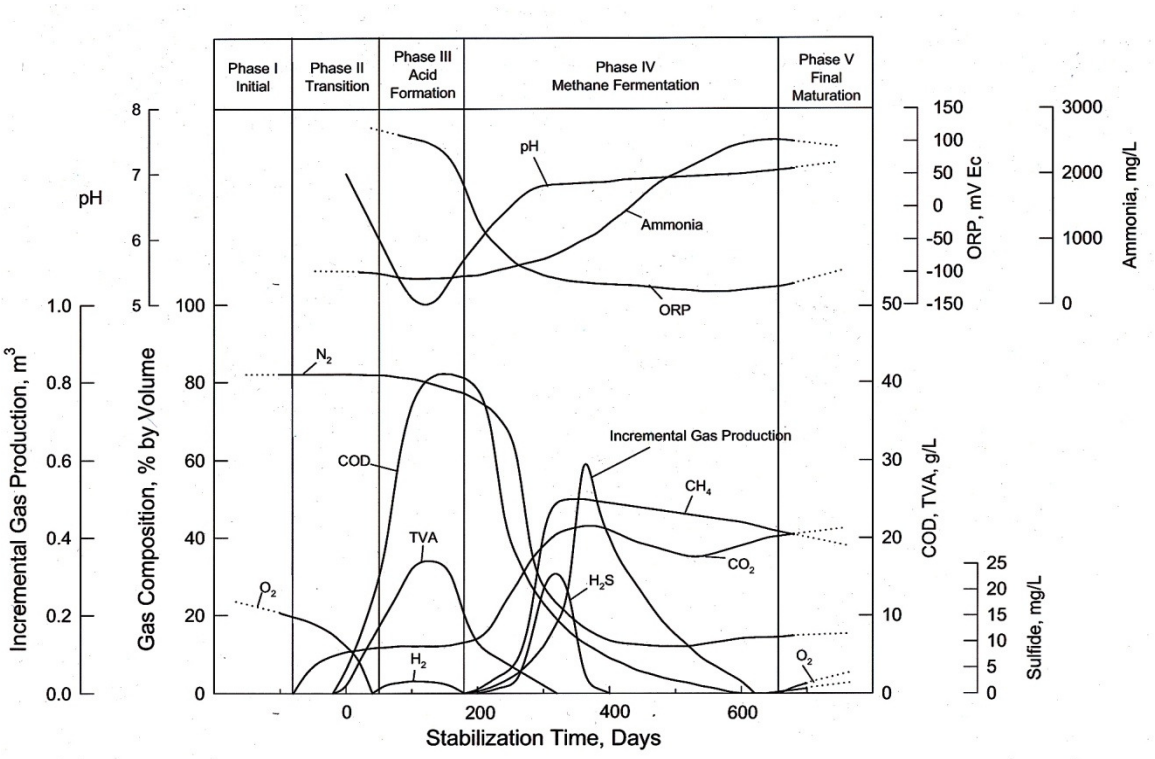
A fundamental concern often associated with conventional municipal solid waste (MSW) landfills is that they remain biologically active for many decades. Conventional landfilling practices are often referred to as a "dry tomb" approach, in which design and operation attempt to minimize liquids entering the waste mass. The waste mass in a conventional landfill is largely organic matter that degrades slowly due to the limited amount of moisture and oxygen in the landfill. Long-term biologic activity can be considered a risk to the environment as a result of landfill gas emissions and potential for release of leachate to the groundwater. Leachate is defined as the liquid that has passed through or emerged from solid waste. To address the concerns with slow rates of degradation and long-term risk to the environment, research, starting in the early 1990's, began to look at alternative to accelerate the decomposition and stabilization process. One such concept that gained significant attention became defined as a "bioreactor landfill". The purpose of this paper is to examine the concept of rapid biological stabilization using the approach sometimes referred to as a bioreactor landfill, or more generically as bio-stabilization. In essentially all instances the acceleration of the decomposition process involves adding large volumes of liquid to the waste mass, typically via leachate recirculation and the addition of liquids from other off-site sources.

The U.S. Environmental Protection Agency (USEPA) defines a bioreactor landfill as "a landfill designed and operated in a controlled manner with the express purpose of accelerating the degradation of municipal solid waste (MSW) inside a landfill containment system." The USEPA also states that "A bioreactor landfill operates to rapidly transform and degrade organic waste. The increase in waste degradation and stabilization is accomplished through the addition of liquid and air to enhance microbial processes. This bioreactor concept differs from the traditional "dry tomb" municipal landfill approach." The Solid Waste Association of North America (SWANA) has attempted to further clarify the definition of a bioreactor landfill as "any permitted Subtitle D landfill or landfill cell where liquid or air is injected in a controlled fashion into the waste mass in order to accelerate or enhance bio-stabilization of the waste." A bioreactor landfill is more than a landfill that simply recirculates leachate. USEPA generally establishes 40 percent moisture content of the waste as the trigger level for specific bioreactor landfill regulations.

Under the Resource Conservation and Recovery Act (RCRA) (40 CFR 257 and 258 (Subtitle D), published in 1991; fully effective 1993) and Nebraska Department of Environmental Quality (NDEQ) Title 132 – Integrated Solid Waste Regulations (Title 132), landfills have been designed and operated for more than a two decades to minimize liquids entering the waste mass during construction, operation, and following closure of the landfill. The philosophy behind Subtitle D regulations was to minimize leachate generation, and as a result landfill gas (LFG) production, by limiting the liquids contacting the wastes. Federal and state regulations allow for the recirculation of leachate and condensate from LFG collection systems into landfills with liners constructed as prescribed by regulation. Both federal and state regulations prohibit the disposal of bulk liquids in conventional landfills. Because of these regulatory restrictions, bioreactor

landfills cannot be considered without special approval by state and federal regulators and then only as demonstration projects. The bulk liquids restriction or "dry tomb" landfill concept discourages liquid from entering the landfill and thus inhibits the decomposition and stabilization of the waste mass. Bioreactor landfills, attempt to enhance stabilization and accelerate the decomposition process through the addition of liquid. Researchers describe waste stabilization proceeding in five sequential and distinct phases (Pohland and Harper, 1986[1]). As shown in Figure 1, the first phase is waste placement. Leachate and LFG generation rates and characteristics vary with each phase and reflect the biodegradation processes taking place within the landfill. In a large-scale landfill, the waste stabilization phases overlap as waste is disposed over a long period of time. The changes in key parameters are shown graphically in Figure 1. Table 1 provides information on key leachate parameters and the ranges in concentration associated with each phase of biodegradation. "Complete stabilization is when the waste material no longer breaks down into byproducts that are released into the environment" (Walsh and O'Leary, 2002[2]). A bioreactor landfill accelerates the waste stabilization process but does not affect the sequence of the stabilization phases.

Figure 1 – Stabilization Characteristics Within a Bioreactor Landfill Unit



The point at which waste degradation is sufficiently complete to consider a landfill "stable" is not clearly defined, and due to the heterogeneous nature of the waste and imperfect biodegradation processes in a large waste mass, a conventional MSW landfill will never reach theoretical stability. Leachate quality and LFG generation are deemed the best indicators of the

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

[2] Walsh, Patrick and Philip O'Leary. June 2002. "Bioreactor Landfill Design and Operation," Waste Age, pages 72 -76.

stabilization process. There is no universally accepted definition of stabilization related to landfills; some researchers and organizations have suggested that sufficient 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) (Reinhart[3]).

Table 1 –Leachate Concentration Ranges as a Function of Stabilization

Parameter	Phase II Transition	Phase III Acid Formation	Phase IV Methane Formation	Phase V Final Maturation
BOD, mg/l	100 – 10,000	1000 – 57,000	600 – 3400	4 – 120
COD, mg/l	480 – 18,000	1500 – 71,000	580 – 9760	31 – 900
TVA, mg/l as Acetic Acid	100 – 3000	3000 – 18,800	250 – 4000	0
BOD/COD	0.23 – 0.87	0.4 – 0.8	0.17 – 0.64	0.02 – 0.13
Ammonia, mg/l-N	120 – 125	2 – 1030	6 – 430	6 – 430
pH	6.7	4.7 – 7.7	6.3 – 8.8	7.1 – 8.8
Conductivity, µmhos/cm	2450 – 3310	1600 – 17,100	2900 – 7700	1400 – 4500

Source: Reinhart and Townsend, 1998[4]. Pohland and Harper, 1986

BOD = Biochemical Oxygen Demand
COD = Chemical Oxygen Demand
TVA = Total Volatile Acids
Mg/l = milligrams per liter
µmhos/cm = micomhos per centimeter (a measure of electrical conductivity)
pH is a measure of acidity
Phase I is the phase where waste is initially placed in the landfill

Current Programs

The technical paper on Municipal Solid Waste Disposal describes the City's current program for managing MSW at the Bluff Road Landfill. The City's current operations include recirculation of leachate and condensate into the landfill for disposal purposes; during periods of heavy precipitation leachate is also hauled off-site for disposal at the City's Northeast Wastewater Treatment Plant. The volume of leachate generated in any given year is a function of several factors, but is largely a function of annual precipitation. As shown in Table 2, annual quantities of leachate generated vary significantly from year to year.

Table 2 –Leachate Generation at the Bluff Road Landfill

Fiscal Year	Total Gallons	Gallons Recirculated	Gallons Treated at City's Northeast Treatment Plant
2007-08	774,241	418,000	356,241
2008-09	631,159	403,750	227,409
2009-10	2,443,207	216,750	2,226,457
2010-11	1,166,035	600,290	565,745
2011-12	1,136,653	969,296	167,357
Totals	6,151,295	2,608,086	3,543,209
Yearly Average	1,230,259	521,617	708,642

[3] Reinhart, D. Active Municipal Waste Landfill Operations: A Bioreactor, National Risk Management Research Laboratory, Office of Research and Development, USEPA.
[4] Reinhart, D., and T. Townsend. 1998. Landfill Bioreactor Design and Operation. Lewis Publishers, New York.

By permit and regulation the City's Bluff Road Landfill is not allowed to take bulk liquids. Landfill operations are designed to prevent stormwater run-on from entering the disposal area and to minimize infiltration of stormwater that falls on the landfill but does not contact the waste; storm water that comes in contact with waste percolates through the waste mass and is collected and managed as leachate.

Generation and Diversion (see Topic Outline)

Typically, liquids additions have been reported to range between 20 and 60 gallons of liquids per ton of waste to bring the moisture content in landfills up to bioreactor levels (Fickes, 2004[5]). It is estimated approximately 50 gallons of liquid per ton of waste would need to be added to obtain a moisture content of 40 percent in the waste mass at the Bluff Road Landfill.

The Bluff Road Landfill accepts an average of 278,000 tons of waste per year, based on the amount of waste accepted over the past five fiscal years. Assuming the need to add approximately 50 gallons of liquid per ton of waste, approximately 14 million gallons per year (approximately 38,000 gallons per day) would need to be added to achieve a full bioreactor condition. It would take a substantial amount of liquid from sources other than leachate generated on-site to conceivably reach bioreactor conditions; the total leachate generated represents only 8.5 percent of the total number of gallons required annually to reach the threshold to operate as a bioreactor landfill. While capturing of incident precipitation may be one source, the supply must be relatively uniform to match waste deliveries and so it would be reasonable to assume that moisture required for a bioreactor operation must come from off-site sources. Obtaining a steady supply of liquids is one reason very few bioreactor landfills are developed, especially in non-costal locations.

An alternate concept is to accept large volumes of liquid for disposal by absorption. This concept would involve less liquid than required to meet the definition of a bioreactor but still take advantage of the added moisture to help accelerate decomposition/stabilization.

Regulatory Considerations

The USEPA provided for pilot projects and a special permit program that would allow for further research and development of the bioreactor landfill technology.

Research, Development, and Demonstration Permits for Municipal Solid Waste Landfills: On March 22, 2004, the final rule of the Research, Development, and Demonstration (RD&D) Permits for Municipal Solid Waste Landfills (40 CFR 258.4, amendment to Subpart A) was published in the Federal Register. The rule became effective on April 21, 2004 and allows owners and operators of MSW landfills to obtain a RD&D permit in approved states to research, develop and demonstrate new methods of managing solid waste in landfills. NDEQ has been granted approval to administer the RD&D rules in Nebraska.

RD&D permits provide a variance from existing landfill requirements for run-on control systems, liquids restrictions, and final cover requirements. The RD&D permit rule contains the following requirements for bioreactor operations:

[5] Fickes, Michael. May 2004. "Bioreactors and Beyond" *Waste Age*.

- No increased risk to human health and the environment
- Demonstration of the following:
  - Groundwater protection
  - Maintenance of no more than 30-cm depth of leachate head on the liner
  - Methods for determining liquid seepage from the landfill
  - Landfill stability
    - Methods for determining geotechnical stability
    - Description of the methods for determining actual or potential movement of waste
- LFG collection and control pursuant to the Clean Air Act (CAA) – National Emissions Standards for Hazardous Air Pollutants (NESHAP) (40 CFR 63, Subpart AAAA)
- Monitoring results submitted at least annually

The RD&D rule allows for a 3-year permit, with permit extensions for a maximum of four 3-year permit terms (12 years total).

Clean Air Act – NESHAP: A MSW landfill must meet the requirements in 40 CFR 63, Subpart AAAA, National Emission Standards for Hazardous Air Pollutants (NESHAP) for Municipal Solid Waste Landfills, and in 40 CFR 60, Subpart Cc, Emission Guidelines (EG), or Subpart WWW, New Source Performance Standards (NSPS) for Municipal Solid Waste Landfills. Besides establishing NESHAPs for MSW landfills, Subpart AAAA requires all landfills defined by Section 63.1935 to meet the Emission Guidelines/New Source Performance Standards (EG/NSPS) requirements of 40 CFR 60, Subpart Cc or Subpart WWW,

The Bluff Road MSW Landfill is currently required to meet the EG requirements of 40 CFR 60, Subpart Cc. If future operations were conducted as a bioreactor, additional landfill gas controls would be required.

Program (Facility/System) Options

There are several different bioreactor landfill technologies currently being tested and demonstrated in the U.S. and throughout the world, including the following:

- Anaerobic
- Aerobic
- Sequential anaerobic-aerobic (hybrid)
- Facultative
- Biological permeable cover
- Flushing

These technologies are further described in Appendix 1. It is beyond the scope of this technical paper to recommend one technology over another. The most commonly used bioreactor or rapid stabilization technologies have been the anaerobic (waste decomposition in the absence of oxygen), aerobic (waste decomposition in the presence of oxygen), and hybrid (aerobic conditions in the upper landfill sections and anaerobic conditions in the lower landfill sections). In addition to full scale bioreactor landfill technology there may be alternatives that do not meet the accepted definition of a bioreactor landfill but attempt to achieve many of the same outcomes; these alternatives may be considered forms of bio-stabilization efforts. Examples of bio-stabilization techniques include:

- Leachate recirculation,

- Liquids addition (below bioreactor levels),
- In-vessel anaerobic digestion (discussed in the technical paper on Waste Conversion Technologies)

Bioreactor technology is an evolving approach to managing MSW landfills. Research into bioreactors began in earnest in the late 1990s. The exact number of landfill projects in the US is unknown; a 2004 estimate identified approximately 20 full-scale bioreactor demonstration projects are under construction, in startup, or in the early stages of operation (O'Brien, 2004[6]).

The potential benefits of full-scale bioreactor (and to a less extent bio-stabilization) operations include the following:

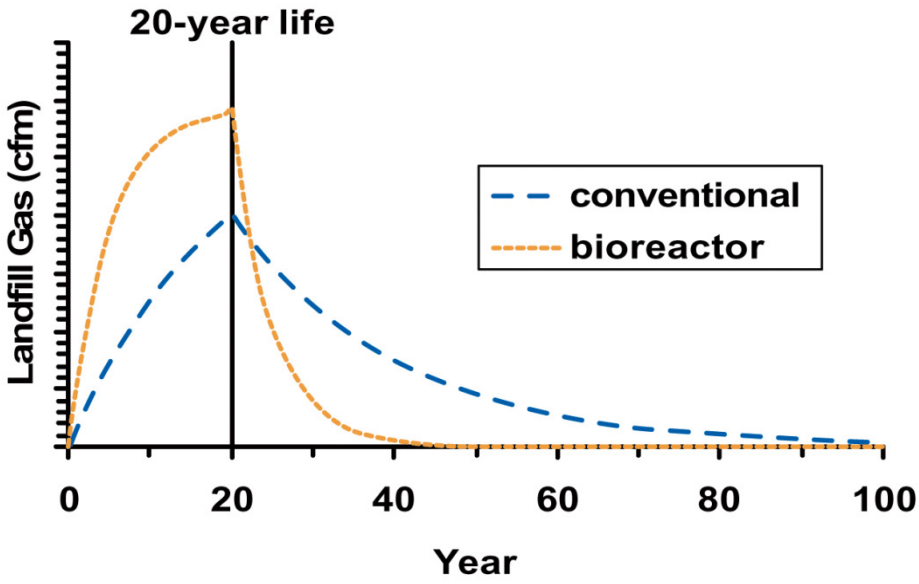
- Recovered landfill airspace, which effectively extends landfill life.
  - Retrofitted existing landfill cells are estimated to recover 15 to 30 percent of MSW landfill airspace (Hater, 2003).
  - New construction cells are estimated to recover 30 to 50 percent of MSW landfill airspace (Hater, 2003).
- Increased revenue opportunities; both for long-term waste disposal and short-term liquids disposal.
- Landfill stability in less than the 30-year post-closure care period.
- Reduced long-term pollution potential associated with leachate and LFG.
- Eliminated (or reduced) off-site leachate treatment/disposal costs.
- Improved leachate quality as the waste stabilizes.
- More landfill-gas-to-energy potential (short-term).
  - Greater LFG generation rate earlier in the life of the landfill. Research suggests that LFG generation rate is 2 to 10 times the rate associated with conventional landfills.
  - Significantly reduced LFG generation rate 10 years after closure, with potential reduction to post-closure LFG collection and monitoring costs (see Figure 3).

With leachate recirculation and limited liquids addition (less than full bioreactor operation), several of these benefits may also be realized but to a lesser degree. As noted above, later retrofitting of landfill cells may extend landfill life by 15 to 30 percent (versus 30 to 50 percent for new landfill cells). For Midwest landfills, including the Bluff Road Landfill, recirculation of leachate and limited additions of moisture from other off-site sources may be more commonly used for liquids disposal (disposal by absorption) as opposed to rapid stabilization of the landfill.

Each bioreactor technology requires moisture additions, which can include leachate, biosolids, and/or other acceptable liquids. Bioreactor landfill technology and bio-stabilization techniques accelerate the biological decomposition of organic wastes by optimizing the conditions necessary for their decomposition. In general, the optimum conditions for waste decomposition include waste moisture content of 35 to 45 percent by weight and temperatures between 120 ºF and 160 ºF.

[6] O'Brien, Jeremy K. 2004. "The Solid Waste Manager's Guide to the Bioreactor Landfill." *MSW Management, MSW Elements*

Figure 3 – Modeled Behavior of Conventional and Bioreactor Landfills



Source: Recreated from graphic in Waste Management presentation to NDEQ, 2003.

Options Evaluation

Bioreactor landfills are technically viable, with many benefits but with limits to their applicability. Site specific aspects that may limit applicability of the bioreactor technology can include:

- Insufficient quantities of liquids
- Absence of consistent sources of liquids
- Absence of an active gas collection system (note: Bluff Road Landfill has an active gas collection system, but currently only in closed areas of the landfill).
- The landfill owner's preference to avoid additional bioreactor construction costs and operational issues
- An abundance of landfill airspace and available land in the region at a low capital cost.
- Neighborhood concerns with odor

If the City of Lincoln were to consider the bioreactor landfill technology now or in future landfill construction, the issues that would need to be addressed include:

- Risk
- Regulatory compliance and permitting
- Design evaluation (calculations) and facility features (required for permit approval)
- Construction considerations (liquids storage/handling/distribution equipment and monitoring systems)
- Liquid quantities, sources and storage requirements
- Operational changes (including monitoring and record keeping)
- Optimizing site life
- Post-closure (care and duration)
- Costs implications (initial costs, increased operating costs, cost recovery, added revenues)
- Managing odors and emissions

Additionally, NDEQ has maintained that any facility permitted under the RD&D rules should have a research purpose and have suggested that purpose needs to be different than bioreactor/bio-stabilization research underway in other landfills.

Typically, bioreactor landfills will cost more to construct and operate. The investment in added capital and operating costs may be off-set by fees charged for liquids disposal, added revenue (long-term) based recovered air space which can increase the overall tonnage disposed over the life of the site, and reduced long-term (post-closure) care costs, due to reduced gas generation and weaker leachate characteristics, which may translate into lower disposal rates (assumes wastewater treatment plant charges fees based on both volume and BOD and COD characteristics).

Consistent with the evaluation criteria developed for use in the Solid Waste Plan 2040, bioreactor/bio-stabilization landfill options have been evaluated based on the following considerations:

- **Waste Reduction/Diversion:** Landfilling is used to manage the waste not otherwise diverted from disposal. As such, landfills are not a waste reduction or diversion program. While bioreactor/bio-stabilization techniques would extend the life of the existing Bluff Road Landfill it will not reduce the amount of waste disposed.
- **Technical Requirements:** The bioreactor technology would likely increase the useful life of the existing and any new landfill, especially if it contains high levels of organic matter. Landfills provide a high degree of flexibility in accommodation changes in waste volumes and composition. The technology utilized for modern landfills is considered reliable and has been deemed protective of the environment by the USEPA. The issues, concerns and uncertainty often discussed in association with a landfill is what risks the site may pose beyond the required 30-year monitoring and maintenance period after site closure. The bioreactor technology targets reducing those risks by accelerating decomposition, reducing long-term landfill gas generation and improving the characteristics of the leachate, which in turn would reduce the risk for impacts to the groundwater.
- **Environmental Impacts:** Landfills are currently considered a necessity in the solid waste management system to protect human health and the environment. The bioreactor technology increases the emissions of greenhouse gases from the landfill, most notably methane and CO2, with a goal of capturing and destroying a significant portion of the methane, which can also be used to generate electricity and off-set emissions from other sources. In contrast to conventional “dry tomb” landfill strategies, bioreactor landfill technology attempts to digest organic matter as opposed to sequester carbon that might otherwise result in air emissions. Additionally, the bioreactor landfill technology attempts to reduce the toxicity of the leachate with a goal of reducing long-term risk to ground water in the event of a release to groundwater. Monitoring of groundwater is a routine part of landfill operations and a permit compliance requirement and is required to continue for 30-years after site closure. Potential health and safety aspects of a bioreactor landfill are not considered significantly different than conventional landfill technologies, but increases in landfill gas and leachate production will require added monitoring and management (added construction and operating costs).
- **Economic Impacts:** The initial construction and ongoing operation, as well as monitoring and reporting costs, will be higher than a conventional landfill. The investment in added capital and operating costs may be off-set by fees charged for

liquids disposal, added revenue (long-term) based recovered air space, reduced long-term (post-closure) care costs, increased short term gas sales revenue (assuming available market), and reduced long-term leachate disposal costs based on weaker leachate characteristics, which may translate into lower disposal rates (assumes wastewater treatment plant charges fees based on both volume and BOD and COD characteristics). These are typically paid from the tipping fee charged to site users. Residents and businesses pay landfill costs through their refuse collection fees. Landfills are not considered a tool for economic development; however the availability of the energy recovered from the landfill gas may be a consideration in attracting new businesses.

- **Implementation Viability:** Implementing the bioreactor landfill technology may be more complex than simply permitting and constructing such landfills in the Planning Area. Issues that are likely to be raised in the siting and development may include: increased costs, odors, permitting (state and local), increased traffic (if additional liquids are delivered in tanker trucks), and environmental risks. From a technical perspective a sustainable source of liquids would need to be identified; this is not considered a technology that can be used off and on as liquids are available. Currently, the maximum period for a bioreactor landfill is 12 years; there is no certain future on continued use of the bioreactor landfill technology.

Relationship to Guiding Principles and Goals

As it relates to the Guiding Principles and Goals of the Solid Waste Plan 2040, the application of the bioreactor or bio-stabilization technologies is only relevant to the maintaining the availability of a local MSW landfill as further noted below:

- **Emphasize the waste management hierarchy**: while landfilling may be considered a lesser preferred option on the waste management hierarchy it nonetheless is recognized as an option where reduction, reuse, and recycling (composting) do not eliminate all wastes from disposal. The utilization of bioreactor and bio-stabilization technologies are not specifically a part of the hierarchy except to the extent that they extend the life a landfill.
- **Encourage public/private partnerships**: Currently the City's role in providing a MSW disposal site is based on fulfillment of state law and Lincoln Municipal Code as well as LPlan 2040. The utilization of bioreactor and bio-stabilization technologies do not specifically relate to a public/private partnership.
- **Ensure system capacity:** Additional MSW disposal capacity is anticipated to be required before the end of the planning period (reference technical paper on Municipal Solid Waste Disposal). The utilization of bioreactor and bio-stabilization technologies could play a role in a strategy to establish and ensure additional disposal capacity by extending the life of existing or future disposal sites.
- **Engage the community:** Public education to engage the community will be important in any effort to modify the current landfill permit or to undertake a lateral expansion of the disposal area. The utilization of bioreactor and bio-stabilization technologies will create additional issues in the permitting process; additional research would need to determine how the public might view these techniques in the framework of permitting a new landfill or lateral expansion of the existing site. In terms of siting and obtaining added landfill capacity, an informed public will be important to understanding why approval of such a facility is necessary.

- **Embrace sustainable principles:** While resource recovery, reuse, waste minimization and waste diversion from landfills are often key aspects of sustainability programs, for waste that is not otherwise diverted or does not provide a viable resource recovery option, landfills can serve to protect the environmental and prevent social impacts. If the increased gas generation associated with these bio-stabilization technologies can be captured and the long-term liability can be reduced, then the utilization of bioreactor and bio-stabilization technologies may have some role in future landfill management. Again, this pre-supposes all of the economic and environmental challenges can be overcome.

Summary

Bioreactor and bio-stabilization technologies accelerate decomposition and stabilization of landfilled waste and have the potential to reduce long-term risks, in comparison to conventional "dry tomb" MSW landfills. They also provide an opportunity to increase the quantity of waste placed within a given landfill space. In essentially all instances the acceleration of the decomposition process involves adding large volumes of liquid from sources other than the liquids generated from the landfill operation. Both federal and state regulations prohibit the disposal of bulk liquid wastes in conventional landfills. Because of these regulatory limitations, bioreactor landfills cannot be considered without special approval by state and federal regulators, and then only as demonstration projects.

The "dry tomb" landfill concept discourages liquid from entering the landfill and thus inhibits the decomposition and stabilization of waste. Bioreactors, on the other hand, attempt to enhance stabilization through the addition of liquid and the acceleration of the degradation process.

Using the 278,000 ton per year average for waste currently being landfilled at the Bluff Road Landfill, it would take a total liquid addition of approximately 14 million gallons per year (approximately 38,000 gallons per day) to achieve a full bioreactor condition. Based on annual leachate generation rates it would take a substantial amount of liquid from other off-site sources to conceivably reach bioreactor conditions.

RD&D permits provide a variance from existing conventional landfill requirements for run-on control systems, liquids restrictions, and final cover requirements; the RD&D permit rule also contains additional requirements related to operations and monitoring. The RD&D rule allows for a 3-year research and development permit, with permit extensions for a maximum of four 3-year permit terms (12 years total).

Issues that would need to be evaluated in further considering implementation would include: potential for increased revenues, benefits of accelerating site stabilization, odor controls, increase landfill gas production, and added costs for construction and operation.

Appendix1

Bioreactor Landfill Technologies

Bioreactor landfill technology accelerates the biological decomposition of organic wastes by optimizing the conditions necessary for their decomposition. Optimal conditions for decomposition include waste moisture content of 35 to 45 percent by weight and temperatures between 120 ºF and 160 ºF.

There are several different bioreactor landfill technologies including:

- Anaerobic
- Aerobic
- Sequential anaerobic-aerobic (hybrid)
- Facultative
- Biological permeable cover
- Flushing

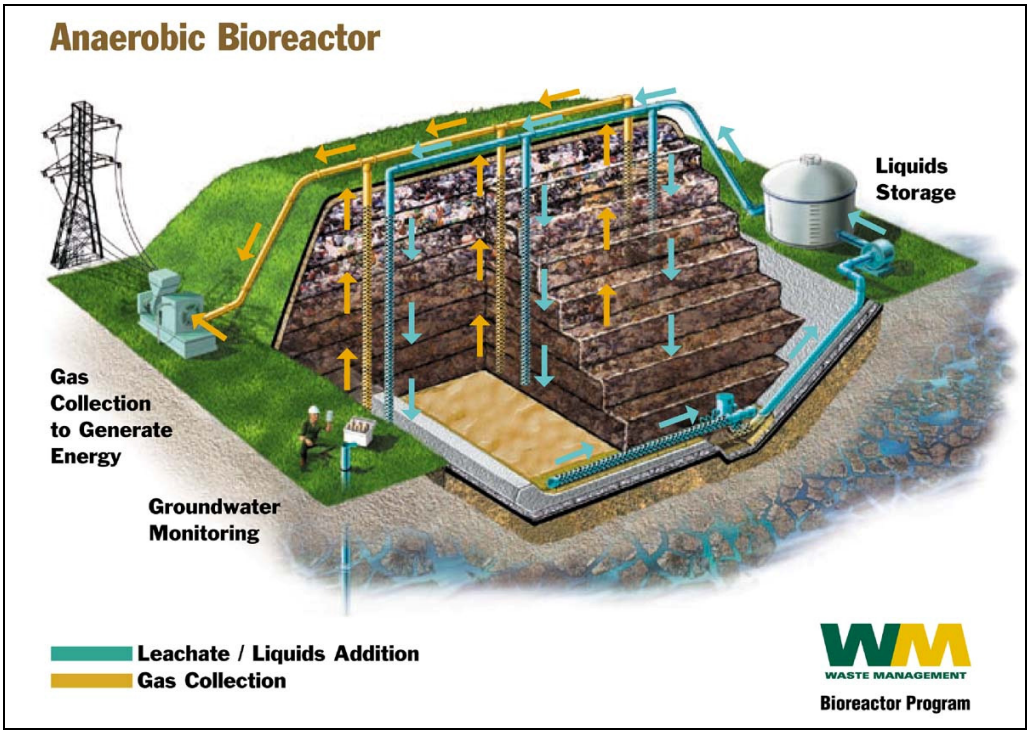
The most commonly used bioreactor or rapid stabilization technologies have been the anaerobic (waste decomposition in the absence of oxygen), aerobic (waste decomposition in the presence of oxygen), and hybrid (aerobic conditions in the upper landfill sections and anaerobic conditions in the lower landfill sections). Insufficient research exists at this time to quantitatively identify the differential percentage of airspace gained between an anaerobic, aerobic, and hybrid bioreactor. Each bioreactor technology requires liquids additions, including leachate and other acceptable liquids.

Anaerobic Bioreactor

In an anaerobic bioreactor, biodegradation of the waste occurs in the absence of oxygen and produces LFG (methane) faster than a conventional landfill, aerobic bioreactor, or hybrid bioreactor (see Figure 1). Anaerobic conditions can also produce more odors. Both LFG and odors require management.

Waste biodegradation occurs at a slower rate in the anaerobic bioreactor than the aerobic or hybrid bioreactor. Waste mass temperatures may be monitored to track the bioreactor progress toward reaching the optimum temperature range. The anaerobic bioreactor method has the most similarities to conventional landfilling, except with higher quantities of liquids addition (beyond levels achieved with leachate recirculation) and increased LFG production.

Figure 1 – Anaerobic Bioreactor



Source: Waste Management, Landfill Bioreactors: What's the Impact?, August 2003.

Aerobic Bioreactor

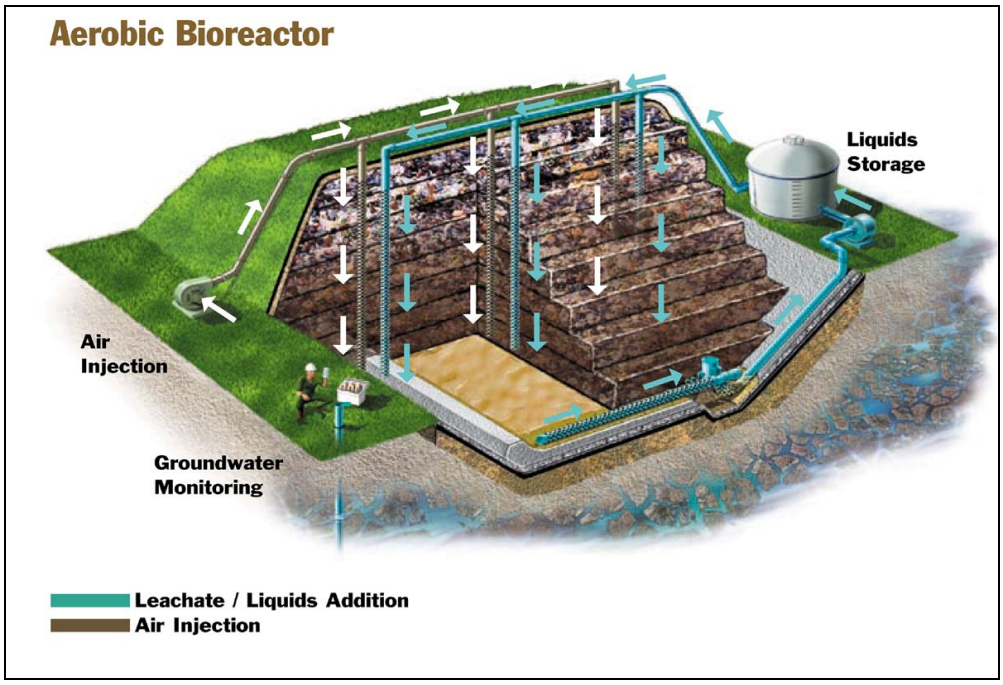
Aerobic biodegradation occurs in the presence of oxygen. In an aerobic bioreactor, air is injected into the waste mass using vertical wells and/or buried horizontal piping systems to promote the aerobic activity (see Figure 2). Similar to most well-run yard waste composting systems, aerobic reactions within a landfill provide rapid biodegradation, prolonged higher temperatures (greater than 142 ºF), reduced methane gas production, and reduced odors. The rapid waste biodegradation produces heat and, combined with the presence of oxygen injection, increases the risk for fires in the aerobic bioreactor landfill. Monitoring of waste mass temperatures is necessary to prevent fires. Aerobic conditions can be difficult to maintain uniformly in a bioreactor landfill. However, this technology provides the greatest acceleration of waste decomposition.

Sequential Anaerobic-Aerobic Bioreactor

The sequential anaerobic-aerobic bioreactor, also known as the hybrid bioreactor, accelerates waste degradation by liquids addition followed by periodic air injection in the upper sections of the landfill (see Figure 3). The aerobic process is often used to accelerate the heat generation process necessary to sustain biodegradation. Once temperatures are established and degradation is progressing, air injection may be terminated and anaerobic processes are allowed to take over. Termination of air injection is also monitored and controlled to prevent spontaneous combustion and landfill fires. The hybrid bioreactor has more rapid waste biodegradation than the anaerobic bioreactor and greater LFG (methane) generation than the

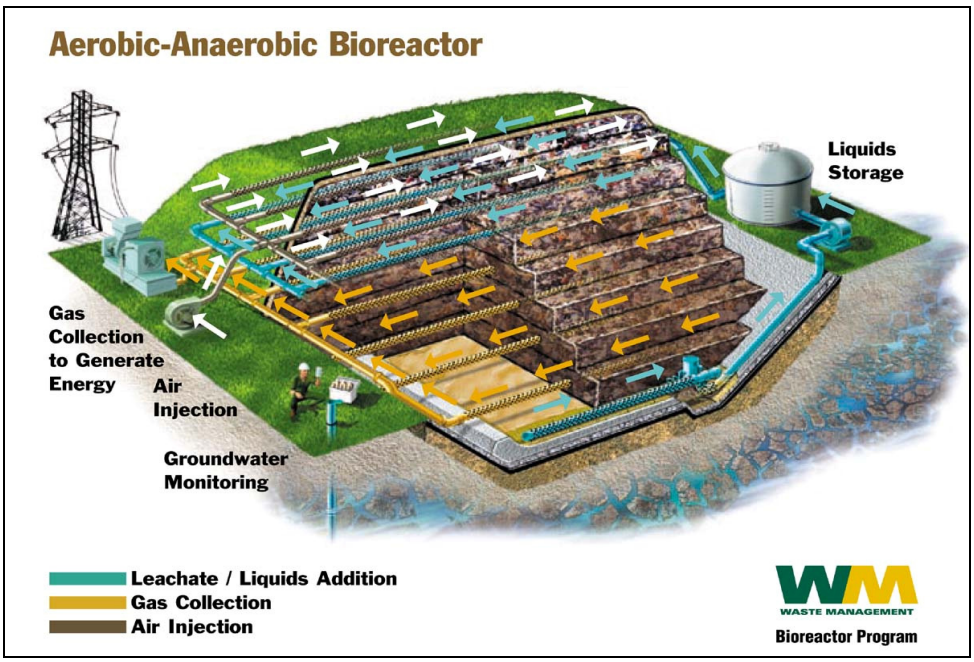
aerobic bioreactor. LFG will be primarily produced in the lower (anaerobic) sections of the landfill and will need to be collected.

Figure 2 – Aerobic Bioreactor



Source: Waste Management, Landfill Bioreactors: What's the Impact?, August 2003.

Figure 3 – Anaerobic-Aerobic (Hybrid) Bioreactor



Source: Waste Management, Landfill Bioreactors: What's the Impact?, August 2003.

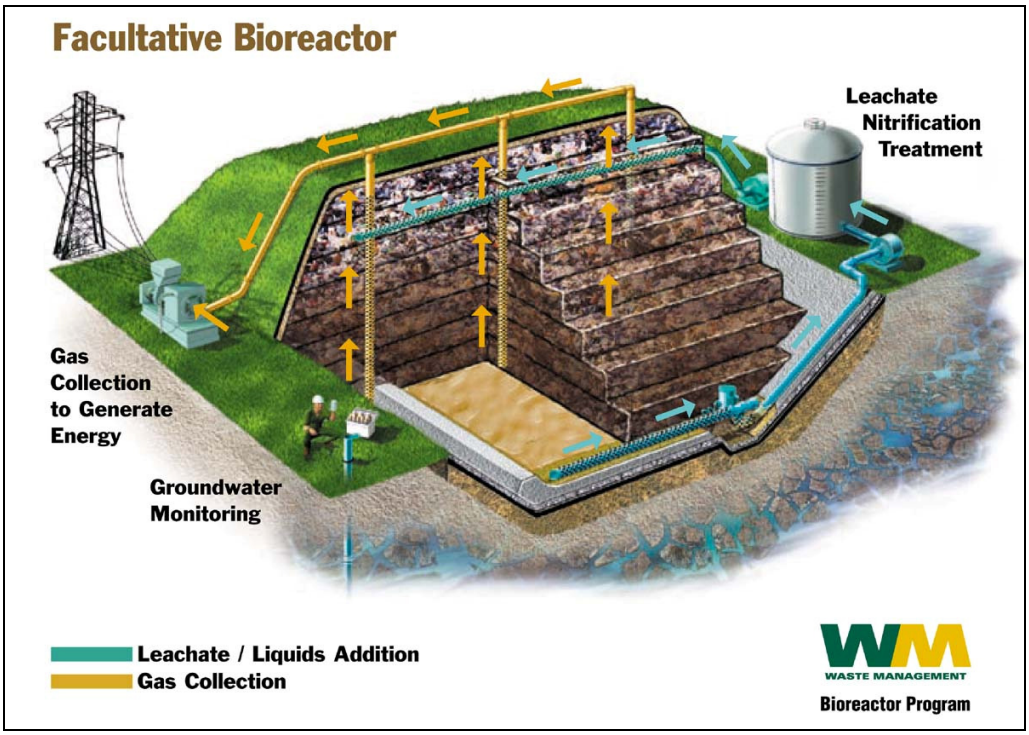
The buried piping distribution system installed in a hybrid bioreactor can serve multiple purposes. Waste biodegradation can be enhanced through cycling the buried distribution lines between liquid distribution and aeration.

Facultative Bioreactor

A "facultative" bioreactor is a landfill that is operated anaerobically and has recirculation of "nitrated" leachate (see Figure 4). Nitrated leachate is leachate that has been treated to convert ammonia to nitrate. Leachate with high ammonia levels (greater than 1,500 mg/kg) can generate odors and inhibit the biodegradation process. Nitrated leachate results when leachate is collected, aerated, and treated (nitrification) in a surface contact biological reactor to reduce ammonia concentrations for better leachate quality (conducive to active biodegradation). The facultative bioreactor has characteristics similar to both anaerobic and aerobic bioreactors.

The piping and design features for a facultative installation are the same as for a landfill operated as an anaerobic bioreactor. The facultative bioreactor may require additional site space and equipment for the leachate treatment system that is not required for the other bioreactor technologies.

Figure 4 – Facultative Bioreactor



Source: Waste Management, Landfill Bioreactors: What's the Impact?, August 2003.

Biological Permeable Cover

Biological permeable cover (BPC) is a landfill cover consisting of permeable material (such as tire chips, geonet, glass cullet, or gravel) underlying a layer of compost or soil capable of supporting vegetation. The cover allows infiltration of rainwater to keep MSW wet for continued

biodegradation, while bacteria in the cover biologically digest the methane produced by the landfill. BPC may be appropriate for areas receiving intermediate cover.

Flushing Bioreactor

An additional bioreactor technology is termed the flushing bioreactor. The concept is to actively encourage degradation in a landfill to breakdown and release the organic pollution load and the waste is then flushed (with high volumes of water) to wash out any soluble degradation products (Beaven & Knox 1999). Costs for the flushing bioreactor, however, may be two to four times higher than the conventional landfill (Karnik & Perry 1997).