BIOREACTOR LANDFILL OPERATION

A Guide For Development, Implementation and Monitoring

Version 1.0 (July 1, 2008)

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Bioreactor Landfill Fundamentals

Background

The Florida Department of Environmental Protection (FDEP) awarded a grant to the *Hinkley Center for Solid and Hazardous Waste Management* to conduct research that supports development and demonstration of bioreactor landfill technology in Florida. The demonstration project was managed by the Hinkley Center in accordance with a Work Plan as required by the FDEP grant award, and involved participation the University of Florida and the University of Central Florida.

The primary goal of the landfill bioreactor demonstration project was to :

Design, construct, operate, and monitor a full-scale landfill bioreactor in Florida in a manner that permits a complete and fair evaluation of this technology as a method of solid waste management in Florida, with appropriate consideration of science, engineering, environmental and economic issues.

A large bioreactor landfill experiment was performed at the New River Regional Landfill to meet this objective. Over time, collaborative efforts with other landfill sites added to the overall project. For information on this project as a whole, the reader is referred to www.bioreactor.org. One of the specific project objectives outlined in the project work plan was: Develop standardized design and operation procedures for this technology.

This document, *Bioreactor Landfill Operation: A Guide For Development, Implementation and Monitoring,* was produced to help meet this objective. The intent of this guide is to provide information useful for landfill operators considering implementing bioreactor technology as well as those operating bioreactor landfills. The information contained within is based both on lessons learned as part of the Florida bioreactor demonstration project, as well as knowledge and experience of the authors from other projects around the world. It is important to note that this document is not intended as a design resource. While regulations are mentioned, it is critical that developers and practitioner of this technology consult appropriately regulatory agencies. Finally, just as bioreactor practice continues to evolve, this document will be periodically updated. Input and suggestions on future research are appreciated.

Florida has been a leading state investigating bioreactor technology. Florida required liner systems for MSW landfills earlier than most states, and because of rainfall levels, leachate management was a prominent issue. Multiple landfills practiced leachate recirculation (a major components of bioreactor technology) as early as the late 1980's. The Alachua County Public Works Department began funding the University of Florida in 1989 to explore using leachate recirculation as means of rapidly decomposing landfilled waste. Additional bioreactor funding was later provided by the Hinkley Center and the US Environmental protection Agency. Bioreactor research continues today at the sites.

The Florida Bioreactor Demonstration projection was initiated in 1998, with the design and construction of a controlled bioreactor test area at the New River Regional Landfill in Union County. This first phase of work wrapped up in 2008, but the site continues to implement bioreactor technology. The as-built bioreactor landfill located at the Polk County North Central Landfill has been operated since 2006. Leachate recirculation of this site is all controlled by a state-of-the-art Supervisory Control and Data Acquisition (SCADA) system. The SCADA system, controls and logs leachate flow rates, injection pressures of horizontal injection lines, and total volume of leachate injected into the landfill. The Highlands County Landfill, located near Sebring, Florida, also began practicing leachate recirculation in 1990's with an objective of accelerating waste decomposition.

This photo shows leachate recirculation ponds used as part of bioreactor landfill research in the early 1990's. Ponds were found an effective method for wetting the waste directly underneath the ponds, thus enhancing waste decompositions, but problems with storm water control, floating waste, and gas collection limit this technology in today's more controlled applications.

Bioreactor Landfill Fundamentals

Introduction

A bioreactor landfill is typically thought of as sanitary landfill that uses enhanced microbiological processes to transform and stabilize the readily and moderately decomposable organic waste constituents in a short period of time (typically 5 to 10 years) in comparison to a conventional landfill (typically 30 to 50 years or more). A bioreactor landfill operator strives to control, monitor, and optimize the waste stabilization process rather than simply contain the wastes as required under current regulations. If operated in a controlled and safe manner, bioreactor landfills can provide a more sustainable and environmental friendly waste management strategy compared to standard practices. The bioreactor landfill requires certain system design and operational modifications to enhance and control the stabilization process. These include:

Liquid Addition: The addition of moisture to landfilled waste creates an environment favorable for those organisms responsible for waste decomposition. The moisture available in the waste is usually not sufficient to meet the microbial requirements, so design and operational modifications are needed to add liquids to the landfill waste. Recirculation of leachate is the most common liquid supply, but other moisture sources can also be used.

Air Addition: Another feature proposed for some bioreactor landfills is the addition of air. The addition of air, and thus oxygen, promotes the aerobic stabilization of the landfilled waste. This is the same process that decomposes waste in a traditional waste compost system. Aerobic waste decomposition is a faster process in comparison to anaerobic waste decomposition. The aerobic technique may be helpful for adopting bioreactor technology in cold regions.

Bioreactor Landfill Definitions

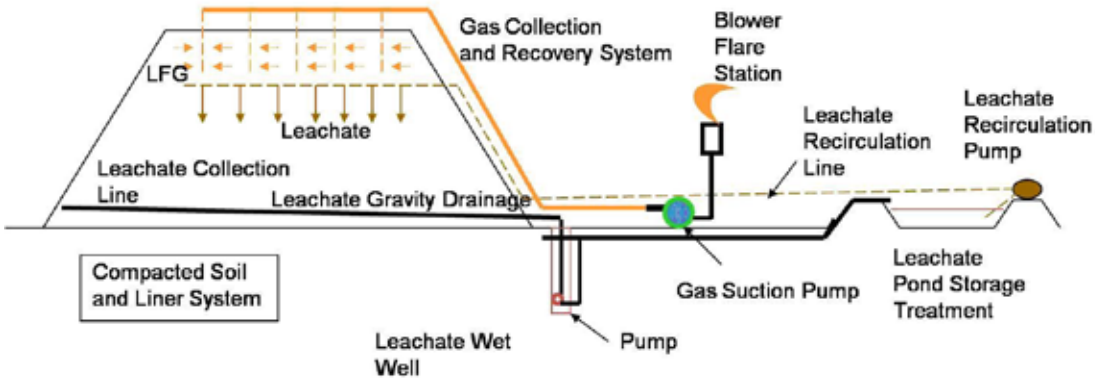
According to the **Solid Waste Association of North America (SWANA),** a bioreactor landfill is:

"a controlled landfill or landfill cell where liquid and gas conditions are actively managed in order to accelerate or enhance biostabilization of the waste. The bioreactor landfill significantly increases the extent of organic waste decomposition, conversion rates, and process effectiveness over what would otherwise occur with the landfill."

The USEPA Clean Air Act regulations (40 CFR 63.1990, **National Emissions Standards for Hazardous Air Pollutants)** define a bioreactor landfill as:

"a MSW landfill or a portion of a MSW landfill where any liquid, other than leachate or landfill gas condensate, is added in a controlled fashion into the waste mass (often in combination with recirculating leachate) to reach a minimum average moisture content of at least 40% by weight to accelerate or enhance the anaerobic biodegradation of the waste."

To accommodate research goals at the Polk County bioreactor, the majority of the injection pipes were separately connected to the liquids distribution manifold outside of the landfill. This allowed valuable data to be collected on horizontal trench performance as a function of depth, configuration and bedding material, but it was problematic in terms of maintenance on the side slopes. Future horizontal trenches at the site will be grouped together as much as possible in the landfill, reducing the numbers of pipes penetrating the landfill slope.



This schematic diagram shows major components of a anaerobic bioreactor landfill including leachate/moisture addition system, gas recovery system, bottom liner system and leachate collection system.

Other Factors: While moisture addition, and to a lesser extent air addition, are the primary technologies for enhancing waste stabilization in controlled bioreactor landfills, other landfill environmental conditions are sometimes proposed for control as well. These includes temperature, pH, and nutrient level. Optimum temperature is known as between 34 to 40°C for the mesophilic microorganisms and up to 70°C for thermophilec microorganisms [1]. In cold regions, low temperatures can be problem, so aerating landfilled waste is used to heat up in the starting phase of anaerobic bioreactor. In operating an aerobic bioreactor, temperature control is critical issue to prevent from catching a fire. pH affects on the activity of methane forming bacteria. The range of 6.8 to 7.4 is known as the optimum pH for the methane forming bacteria [2]. Nutrient and microbe addition is not common, and is generally reviewed as not needed.

Bioreactor Landfill Fundamentals: Classification

As described already, a bioreactor landfill may be defined differently depending on the person, context, or regulatory program. For the purposes of this guide, a bioreactor landfill is a landfill designed and operated in a manner which allows the *controlled* treatment (stabilization) of the solid waste. A common question is "what is the difference between a bioreactor landfill and a landfill that practices leachate recirculation?" Again, from the context of this guide (not necessarily from a regulatory perspective), if a landfill practices leachate recirculation as part of a controlled process to enhance waste stabilization, it is a bioreactor. If leachate recirculation is only practiced as a means to dispose leachate, it is not a bioreactor (though many of the same design and operation issues apply). Other terms used to describe specific types of bioreactors are presented below.

Bioreactor Landfill Terminology

Anaerobic Bioreactor Landfill: In an anaerobic bioreactor landfill, moisture is added to the waste mass in the form of recirculated leachate and other sources to obtain optimal moisture levels. Biodegradation occurs in the absence of oxygen (anaerobically) and produces landfill gas (LFG). Landfill gas, primarily methane, and carbon-dioxide can be captured to minimize greenhouse gas emissions and for energy generation.

Aerobic Bioreactor Landfill: In an aerobic bioreactor landfill, leachate is removed from the bottom layer, piped to liquids storage tanks, and recirculated into the landfill in a controlled manner. Air is injected into the waste mass, using vertical or horizontal wells, to promote aerobic activity and accelerate waste stabilization.

Hybrid (Aerobic-Anaerobic) Bioreactor Landfill: The hybrid bioreactor landfill accelerates waste degradation by employing sequential aerobic-anaerobic treatment to rapidly degrade organics in the upper sections of the landfill and collect gas from lower sections. Operation as a hybrid results in the earlier onset of methanogenesis compared to aerobic landfills.

Semi Aerobic Bioreactor Landfill: A term originated in some Asian countries to describe a landfill where natural ventilation of the leachate collection system promotes aerobic stabilization of the leachate.

As-Built Bioreactor Landfill: A landfill conceived from the beginning (or near the beginning) as a bioreactor; the construction (and perhaps the operation) of the bioreactor components occurs while waste is actively deposited in the landfill. For as-built bioreactor more choices for selecting liquid addition techniques are available in comparison to retrofit bioreactors.

Retrofit Bioreactor Landfill: A landfill that is not originally conceived as a bioreactor; the construction and operation of bioreactor components occurs after landfill operation, and most or all of the waste has been placed. The methods that can be used for liquids addition are limited compared to as-built bioreactors.

Bioreactor Landfill Fundamentals: Benefits

Operating a landfill as a bioreactor offers several potential benefits over a conventional landfill.

Waste Stabilization: The primary advantage of operating a bioreactor landfill is fast waste stabilization, making bioreactor operation a more sustainable waste management option. This in turn relates to several other advantages.

Leachate Treatment, Capital, and Operating Costs: Using leachate recirculation for moisture addition may offer considerable costs savings on leachate treatment. At sites where leachate treatment is not expensive, this advantage may not be significant. At sites with limited leachate managements options, saving could be substantial.

Air Space Recovery: It has been demonstrated that a 15 to 30 percent gain in landfill space, due to an increase in density of waste mass, can be achieved when a landfill becomes stabilized. If the landfill operator structures their sequence to utilize this air space gain, savings can be substantial.

Landfill Gas Generation Rates: In bioreactor landfills, gas generation rates are much higher than conventional landfills, therefore landfill gas can potentially be recovered and used economically.

Environmental Impacts: A bioreactor offers considerable reduction in environmental impacts as the waste gets stabilized in a short span of time, when the landfill is still being monitored and when the landfill infrastructure is in top condition.

Post Closure Care, Maintenance and Risks: Bioreactors have the potential to save on post closure care, maintenance and risk management costs. The landfill is stabilized in a short span of time, therefore the final cover settles and repairs needed reduce maintenance and monitoring costs in comparison to the conventional dry tomb landfills. To date, the regulatory authorities have not reduced the long term monitoring frequency and duration for bioreactors.

Bioreactor Landfill Fundamentals: Concerns

Bioreactor landfills offer several potential benefits, but they can be a cause of concern if bioreactor operations such as leachate recirculation are not performed correctly. A few of the more common concerns are described here. Possible methods of preventing and mitigating these concerns are also described here in brief.

Leachate Seeps: When the liquids are added at a high pressure or at a flow rate higher than the local infiltration rate or absorption capacity of the waste mass, there is a possibility of seeps. Seeps may be observed along the slopes of the landfills where leachate front meets the daily cover due to preferential flow paths and channeling. Leachate seeps are discussed in detail later in this guide.

Landfill Slope Stability: Since liquids are added in the bioreactor, internal pore water pressures have the potential to increase and thus decrease the shear strength of the waste. Excessive pore water pressures can cause slope failures.

Temperature Control: Aerobic waste degradation increases waste temperature significantly. The increased temperature, if not controlled, can cause fires. Temperature rise can be controlled by stopping air injection thereby cutting the source of oxygen, recirculating cold leachate and completely wetting the particular location.

Gas and Odor Control: Gas production is enhanced at bioreactors. If the gas is not controlled, odors and other environmental problems with gas can result.

Fire and Explosions: The primary concern when operating an aerobic bioreactor is the potential for flammability and explosive gas mixtures involving oxygen and methane. The flammability range for methane is between 5% and 14% but this only refers to the flammability of methane with air. When nitrogen and other diluent gases are present, this range is decreased. The other concern with the aerobic bioreactor is spontaneous fire. In an aerobic bioreactor air is injected in the bioreactor to promote aerobic microorganisms to decompose the waste. The aerobic activity generates high temperature. At places due to high temperature and low moisture content spontaneous combustion may occur. So temperature monitoring at different locations and depth of the aerobic landfill is very important.

Bioreactor Landfill Fundamentals: Implementation

When an operator is considering the implementation of bioreactor technology at their site, the following points should be taken into consideration:

Site Configuration: One of the important aspects while considering implementing bioreactor technology is the site configuration. If the cells are designed with large areas but are allowed to attain a limited height, bioreactor technology may not be useful from the prospective of achieving additional air space. With limited cell height only limited settlement can be achieved. However, from the waste stabilization considerations a shallow height landfill may allow uniform distribution of liquids through the depth of landfill, thereby allowing faster stabilization.

Landfills operators considering implementation of bioreactor technology for the landfills located in cold regions may not achieve rapid stabilization of waste. The waste decomposition is carried out by the bugs (microorganisms) and these can be effective in a given environment, and temperature is one of the prime considerations for their operation. Optimum temperature range for anaerobic (mesophilic) organisms is reported between 34 to 40 ^{o}C. For the bioreactors located in cold regions, to increase the temperature, air circulation through the waste may be practiced. Air injection will onset aerobic activity and the aerobic microorganisms can increase waste temperature and kick off the waste degradation process. Once the temperature rises, methanogenic microorganisms can take over and degrade the waste.

Remaining Capacity: If an operator looks for starting a bioreactor at a landfill (or landfill cell) that is left with small remaining capacity (say 2 -3 years), it may not be useful with the prospective of gaining on air space. Also it may be harder to get leachate into the deep areas of the landfill (it may not be possible yo use horizontal lines at lower levels) and get good stabilization of the waste; however, leachate treatment cost can be saved. But for a landfill where the remaining capacity is enough horizontal injection lines can be placed to inject leachate and uniform liquid distribution can be achieved.

Leachate Collection System Design: Federal regulations prescribe a one-foot maximum allowable leachate head on the bottom liner. So in case of bioreactors, leachate collection system must be designed to accommodate the higher volumes of liquids that will be

moving through the landfill. This may require increasing the pipe size at some locations, and additional pumping capacity. The long-term permeability of granular drainage material should be evaluated since the base of the landfill must function during the lifetime of bioreactor operations as there are increased chances of its fouling due to leachate recycling. It may be useful to rely on pressurized drain fields, rather than relying on gravity drainage to maintain desired flow rates. Use of high-density polyethylene (HDPE) pipes shall be preferred due to their strength and durability. While converting an existing landfill to retrofit as a bioreactor, existing leachate collection design should be evaluated to ascertain its adequacy to accommodate the high volumes of leachate.

Gas Collection System Configuration: Generally, gas recovery and collection systems are installed a few years after a landfill cell is completed. But for bioreactor landfills, the gas collection system needs to be installed either during the waste filling in the cell or immediately after cell completion. Moreover, the gas collection system shall be designed for handling higher peak volumes but need to do so for shorter period of time. The design considerations shall also include the pressure buildup condition on geomembrane cap, when the gas collection system is shut down for any breakdowns. Other important aspect in designing and operating gas collection system will be to prevent liquids intrusion into the gas collection wells.

Cover Soil Usage: The effective distribution of recirculated leachate or water in the waste mass is best achieved in a homogeneous waste medium. The presence of continuous low permeability soil layers can impede the moisture flow. This can create slope stability concerns as well as dry pockets of waste. In addition to stability issues, zones of low permeability can cause localized ponding of liquids and leachate breakouts. Use of waste materials with permeability close to that of MSW such as mulch, are potential good options.

Use of alternative covers that do not create such barriers and can mitigate these effects can be helpful. In many cases, alternative covers have been found to be quite cost effective when compared to soil. The possible alternate covers may be in the form of blankets, sprays or any other alternate material. The blanket covers may be in the form of tarpaulins that can be laid after the day's landfilling process and can be removed next morning. The sprays can be either slurries or foams. Slurries are solids mixed with

water. Commercially available slurries utilize newspaper, mixed paper, wood fibre, cement kiln dust, or fly ash, along with mixing agents and water. Foams are comprised of synthetic materials, such as resin or soap that are mixed with water. The use of alternate daily cover shall be selected based on cost benefit economics.

Waste Stream Characteristics: As mentioned earlier, a homogeneous waste mass can help uniformly distribute the liquid. For that reason, it may be helpful, if the waste stream does not contain appreciable amounts of tires, yard waste, lumber, tree trunks and limbs, bulky waste, sludge, ash, household hazardous wastes, or shingles etc. These wastes should be intercepted and directed for on-site or off-site processing and disposal by means other than landfilling. Waste segregation may include separation of construction and demolition (C&D) wastes from the MSW stream.

Pre-processing of waste like shredding, recycling and segregation etc. (with the intent of increasing organic content and high exposed surface area) before placing in a landfill may be useful to promote uniform moisture distribution and reduce differential settlements. Limited shredding can be obtained by spreading refuse in thin lifts and using landfill equipment to break open plastic bags and break down containers. Mechanical shredding can be efficient and effective in reducing particle size; however it is a labor intensive and high-cost activity, which may not be cost-effective.

Waste shall be placed in the landfill with reduced compaction, so as to promote leachate recirculation. The reduced compaction can be achieved by limiting the number of passes of the compactor over the waste. Alternatively, light compaction equipment can be used for leveling the waste. The waste will ultimately settle as a result of moisture addition, the weight of overlying layers, and waste degradation, therefore airspace lost due to initial placement with low compaction may be recovered with time.

Bioreactor Landfill Fundamentals: Regulations

There are no specific federal regulations for bioreactor landfills. MSW landfills in the US are regulated as part of several federal regulations. Minimum standards for MSW landfill design, construction, and operation are regulated under Subtitle D of the federal Resource Conservation and Recovery Act (RCRA) under Title 40 of the Code of Federal Regulations, Part 258 (40CFR258). Among other things, these rules contain location restriction for where a landfill unit may be constructed, design requirements for liners and leachate removal systems, groundwater monitoring requirements, and the need for financial assurance.

Bioreactor landfills, like conventional landfills, must abide by all 40 CFR 258 requirements; however, the term bioreactor is not included anywhere in the rule. Some rule language does specifically address issues relating to bioreactor operations. Under RCRA Subtitle D, bulk liquids are prohibited from landfill disposal; leachate and landfill gas condensate are permitted to be recirculated to the landfill as long as the liner requirements are met.

The Subtitle D rules do have some provisions for gas management, but most of the regulations pertaining to landfill gas are found in rules pertaining to the 40 CFR 60 Clean Air Act (CAA). In short, landfills that surpass a certain mass or volume of waste and that produce more than a threshold amount of non-methane organic compounds (NMOCs) must collect gas. Bioreactor landfills produce greater volumes of gas during and shortly after the active phase of landfill operation. So ideally a gas collection system shall be in place to avoid atmospheric gas emissions much before than a conventional Subtitle D landfill. But according to the CAA landfills that add liquid more than just leachate or gas condensate and reach a moisture content of 40% or more are

According to 40 CFR 248, there are some restrictions to liquid addition:

(a) Bulk or noncontainerized liquid waste may not be placed in MSWLF units unless:

(1) The waste is household waste other than septic waste; or

(2) The waste is leachate or gas condensate derived from the MSWLF unit and the MSWLF unit, whether it is a new or existing MSWLF, or lateral expansion, is designed with a composite liner and leachate collection system as described in § 258.40(a)(2) of this part. The owner or operator must place the demonstration in the operating record and notify the State Director that it has been placed in the operating record.

(b) Containers holding liquid waste may not be placed in a MSWLF unit unless:

(1) The container is a small container similar in size to that normally found in household waste;

(2) The container is designed to hold liquids for use other than storage; or

(3) The waste is household waste.

(c) For purposes of this section:

(1) Liquid waste means any waste material that is determined to contain "free liquids" as defined by Method 9095 (Paint Filter Liquids Test), as described in "Test Methods for Evaluating Solid Wastes, Physical/Chemical Methods" (EPA Pub. No. SW–846).

(2) Gas condensate means the liquid generated as a result of gas recovery process(es) at the MSWLF unit..

According to **Clean Air Act 40 CFR Part 63 – Subpart AAAA—National Emission Standards for Hazardous Air Pollutants** gas collection is required from bioreactors:

(a) If your bioreactor is at a new affected source, then you must meet the requirements in paragraphs (a)(1) and (2) of this section:

(1) Install the gas collection and control system for the bioreactor before initiating liquids addition.

(2) Begin operating the gas collection and control system within 180 days after initiating liquids addition or within 180 days after achieving a moisture content of 40 percent by weight, whichever is later. If you choose to begin gas collection and control system operation 180 days after achieving a 40 percent moisture content instead of 180 days after liquids addition, use the procedures in §63.1980(g) and (h) to determine when the bioreactor moisture content reaches 40 percent.

(b) If your bioreactor is at an existing affected source, then you must install and begin operating the gas collection and control system for the bioreactor by January 17, 2006 or by the date your bioreactor is required to install a gas collection and control system under 40 CFR part 60, subpart WWW, the Federal plan, or EPA approved and effective State plan or tribal plan that applies to your landfill, whichever is earlier.

§ 63.1980 What records and reports must I keep and submit?

g) If you add any liquids other than leachate in a controlled fashion to the waste mass and do not comply with the bioreactor requirements in §§63.1947, 63.1955(c) and 63.1980(c) through (f) of this subpart, you must keep a record of calculations showing that the percent moisture by weight expected in the waste mass to which liquid is added is less than 40 percent. The calculation must consider the waste mass, moisture content of the incoming waste, mass of water added to the waste including leachate recirculation and other liquids addition and precipitation, and the mass of water removed through leachate or other water losses. Moisture level sampling or mass balances calculations can be used. You must document the calculations and the basis of any assumptions. Keep the record of the calculations until you cease liquids addition.

(h) If you calculate moisture content to establish the date your bioreactor is required to begin operating the collection and control system under §63.1947(a)(2) or (c)(2), keep a record of the calculations including the information specified in paragraph (g) of this section for 5 years. Within 90 days after the bioreactor achieves 40 percent moisture content, report the results of the calculation, the date the bioreactor achieved 40 percent moisture content by weight, and the date you plan to begin collection and control system operation.

considered bioreactor landfills for purposes of this rule. Also of interest to note is that the moisture addition must be for the purpose of promoting anaerobic waste stabilization.

The Research, Development and Demonstration (RD&D) Rule was enacted in March of 2004 to amend the provisions of 40 CFR 258 and allow state regulators to issue permits to existing, new or lateral expansion landfills for which the owner or operator proposes to utilize innovative and new methods that vary from the operating criteria of the run-on control systems and liquids restrictions, and the final cover criteria. The U.S. EPA can issue special research, design, and development (CFR 40 258.4) authorization permits to allow other additions of liquids to a bioreactor landfill.

Liquids Addition: Basics

Landfill operators have used several different types of liquids addition systems. The selection of the system employed at a site will be dictated by a number of factors. The type, configuration, and operation of a liquids addition must be approved by the appropriate regulatory agency as part of the site's permit. Landfill operators should consider the following factors and discuss design and constraints with the site engineer as part of the permitting process.

As-built bioreactor or retrofit bioreactor: The type of system used for a retrofit bioreactor will typically be more limited than an as-built bioreactor because the waste is already in place and the landfill may not have been originally designed with liquids addition in mind. Horizontal trenches are not appropriate for deep retrofit landfills, and thus vertical wells may be needed to adequately distribute moisture. The volume and rate of liquids addition may be limited with retrofit bioreactors to address capacity issues with the leachate collection system.

Installation and Infrastructure: Surface application techniques such as infiltration ponds and the use of tanker trucks may be a less expensive in comparison to the subsurface techniques for small operations. But for large landfills, subsurface application techniques may be necessary to effectively wet the waste. Availability of equipment (like excavators and drill rigs) at the landfill can be another controlling factor in selecting a liquid addition method. Some operators prefer to construct liquid addition infrastructure on their own, while others hire outside contractors to do the work.

What type of liquids can be added?

Research and experiences have shown that if the moisture content of waste is increased (compared to normal dry conditions), biological decomposition can be enhanced. Several different sources of moisture have been used at the landfill sites. Note: The type and amount of liquids you can add depends on what the landfill is permitted for under the relevant regulations.

Leachate is typically pumped from the storage system (e.g., tank., pond) to the landfilled waste. In some cases, the system may be designed, so leachate can be recirculated from the landfill's pump station. While leachate is most commonly recirculated back to the landfill from which it originated, sometimes leachate originating from another landfill can be added as well (check permit!).

Gas condensate is normally managed by combining with leachate, so gas condensate will also serve as a liquid source at bioreactor landfills.

Some landfills have been permitted to use **groundwater** or **surface bond** as a source of moisture. The water amount estimated for some bioreactors is so large that leachate alone does not provide sufficient volume.

Biosolids, the term commonly used for municipal sewage sludge, contain a large amount of moisture and thus serves a moisture source for some landfills. In a similar manner, **industrial wastewater** and **sludges** are also sometimes accepted at bioreactor landfills. Landfills wishing to add these waste streams as a moisture source must seek special regulatory permission.

Interference with daily operations: The installation of liquids addition devices can have a great impact on daily landfill operations. If horizontal trenches are installed as the landfill is filled, there is a limited time window for construction. In such cases, installation may require traffic to be routed or internal roads to be trenched. Excavated waste must also be managed by transporting to the active disposal or by compacting and covering in place.

Techniques of Liquid Addition

Surface Systems

- Spray irrigation
- Drip irrigation
- Tanker truck application
- Infiltration ponds
- Leach field
- Surface trench

Subsurface Systems

- Vertical injection wells
- Horizontal trenches
- Buried infiltration galleries
- Combination of horizontal lines and vertical wells

Sources of liquid: If high solids liquid sources such as biosolids are a source of moisture for the bioreactor, surface application will be required. If low solids liquids such as leachate and groundwater are used, then vertical wells or horizontal trenches are used.

This photo shows biosolids being co-disposed with MSW. Biosolids represent a possible source of moisture for bioreactor landfills. To meet federal regulatory requirements, biosolids must first be dewatered to pass the paint filter test (a moisture content of 80%-85%). Some bioreactor landfills have received special regulatory permission to add biosolids that have not been dewatered.

Other Site Considerations: Many other factors will play a role in the selection of a liquids addition approach and its design. Factors that a design engineer should incorporate into the decision-making process (in consultation with the landfill operator) include site configuration and layout, waste and cover soil characteristics, gas system layout, and stormwater management. Experience has found that it is more difficult to add liquids to waste at greater densities. More pressure is required to distribute liquids into deeper landfills. The selection and placement of cover soil can have a major impact on liquids movement: low permeability soil will block moisture movement, possibly resulting in more seeps and need for more recirculation devices. If an alternative daily cover created from construction and demolition debris is used, odors may be more of a problem because of hydrogen sulfide formation. Liquids addition can have a major impact on gas collection, such as flooding of gas wells. Because seeps are more prominent in wet landfills, proper and efficient stormwater control is important.

Liquid Addition: System Configuration

Many factors will be considered by an engineer when designing a liquids addition system. Here is an overview of the considerations the operator can discuss with the design engineer.

In simple terms, three components are needed to add liquids to landfill unit:

- a liquids storage unit
- a conveyance mechanism to deliver liquids from the storage unit to the landfill unit
- a scheme to apply liquids to the landfilled waste mass (the liquids addition system)

Storage systems include ponds and tanks, located outside the lined landfill area. Liquids can be delivered from the storage system to the landfill in a variety of fashions. Liquids can be hauled to the landfill in a tanker truck and discharged directly to the working face or to an impoundment area. Liquids can be delivered through a piping network to the points of interest. Once delivered to the landfill, liquids can be applied to the landfilled waste using a number of techniques. These will be described in more detail.

Again it is important to note that the type of system ultimately used at a landfill site will depend on many factors the engineer considers during the design process and that the system must be approved by the appropriate regulatory agency during the permitting process.

How Much Water Should be Added?

One of the decisions the engineer designing the liquids addition system will make is the amount of moisture that needs to be added. It is common practice to add enough liquids to raise the initial moisture content to a final target such as field capacity. Field capacity is the moisture content the waste can "hold" before without draining. Bioreactor landfill operators should be aware that this volume is large. The following table provides the gallons of moisture needed for every wet ton of waste to raise the initial moisture content to a specified target. For example, a landfill receiving 1,000 tons per day would need to add approximately 55,000 gallons of water per day to raise the waste moisture content from 20% to 35%. While other factors will be considered in the design of the liquids addition system (water contributed by rainfall, areas of the landfill targeted for wetting), a take-home message for operators is that the moisture volume needed may not be available from existing leachate alone.

Volume of liquid required in gal/ton of waste			
Initial M.C. *	Target Moisture Content (%)		
	30	35	40
15	51.4	73.8	99.9
20	34.3	55.3	79.9
25	17.1	36.9	59.9
30	-	18.4	40.0

* by wet weight

Liquid Addition: Surface Addition System

Surface addition techniques include those where the liquid is applied to the landfilled waste by application to the landfill surface. In surface systems, the driving forces for liquids into the landfill are gravity, suction forces by the waste, and perhaps some small depth of ponded liquid. This contrasts to subsurface systems where pressure is used as a driving force for liquids distribution. In some cases, liquids are added directly to the waste as it is disposed, while in other cases the liquids can be added to the surface of daily or intermediate cover materials. When liquid is applied at the surface of a landfill, a part of the liquid may evaporate, with the remaining leachate infiltrating into the underlying solid waste. Surface application is most often employed at landfills without a cap, but in some cases liquids have been introduced to the surface of the waste underneath the cap but above the surface layer of the waste using trenches, leach fields, or drip lines.

Direct wetting of the working face: Tanker trucks are often used to carry leachate to the working face. The leachate is discharged by a hose or spray nozzle. Since many landfills are already equipped with water wagons for dust control, direct application can be a low-cost, easy-to-implement method. Leachate can be sprayed or pumped onto the waste as it is unloaded and compacted on the working face. Direct application of the leachate provides for good liquids distribution in the areas where it is applied. Major concerns that must be addressed with this method is prevention of off-site leachate runoff and contamination of storm water.

Spray or drip irrigation: Using spray irrigation, leachate can be applied to the waste as it is being disposed of or to areas where the landfilled waste is already covered. Application rates should be maintained low enough to avoid runoff. The objective of spray application is often to reduce leachate volume through evaporation. Thus it may not be useful if the primary objective is to increase the waste moisture content. Spraying is accomplished using portable spray heads that can be moved around the landfill as the working face progresses or with a more permanent system for areas that will remain inactive for some time. One issue of concern that required evaluation is potential exposure of worker and customers to leachate added.

In drip application, drip hoses or pipes are placed at the surface of the landfill, either directly on the waste before cover placement, or in a more permanent leach bead,

such a gravel or shred tires. Drip application, if well designed, can provide for relatively uniform liquids distribution at the surface of the landfill. Drip application should not pose the same problems with aerosol dispersion as spray application.

Infiltration ponds: Surface ponding was one the first leachate recirculation methods applied in Florida. Ponds were excavated a shallow depth into the waste or they were constructed by compacting earthen berms to form the pond walls. Ponds can be an effective method for wetting the area under the pond, but the exposed leachate poses problems with respect to control of stormwater, gas control, and exposed waste.

Infiltration trenches: Trenches excavated at the surface of the landfill are sometimes used to distribute the liquids into the upper layers of the waste mass. The trenches are typically fitted with a liquids distribution pipe and backfilled with a porous media. Trenches used at other landfills have ranges in depth from 3 to 15 feet into the waste.

Common concerns: surface application systems are generally limited to smaller leachate application rats compared to subsurface systems. Concerns common to surface systems include formation of aerosols and their exposure to workers, off-site migration of contaminants with storm water runoff, and gas emissions from the liquids application area. Surface application systems depend on the ability of liquids to migrate from the surface of the landfill in to the underlying waste under gravity. Such systems also permit gas escape to the environment. Fore most bioreactors, surface application system will be one tool used to add liquids in addition to subsurface application approaches.

Liquid Addition: Sub-surface Addition System

Vertical wells were drilled at the New River bioreactor. Small diameters pipes (PVC; 2 inches in diameter) were placed into holes constructed with an open-flight rotary auger (4.5 inches in diameter). Wells were placed in clusters of three (with screened sections at three different depths). Approximately 50 total clusters were constructed in a grid of 50-ft spacing.

In sub-surface systems, the liquids are added to the landfill using a system located within the waste. Liquids can be added under pressure. The pressures that can be applied will be determined as part of the design and permitting process. Pressure can be maintained by a pump or by a standing head of liquid. The addition of leachate under pressure promotes distribution of liquids to areas otherwise inaccessible. Subsurface systems may be grouped as vertical and horizontal systems. These can also include a combination of techniques (vertical wells connected to horizontal layers). These devices are installed either while waste is being placed in the landfill (deep horizontal trenches) or after the waste has reached its final grade (shallow horizontal trenches, vertical wells).

Vertical Wells

In this type of liquids addition system, a number of vertical wells are constructed across the depth of the landfill. Previous reported applications have used well diameters ranging from 2 inches to 4 ft. Vertical well systems most commonly encountered with retrofit bioreactors. Vertical wells for liquids introduction are most commonly constructed by drilling into the waste. Large-diameter wells of 1 to 3-foot diameter can be drilled using bucket augers. Many of the earlier liquids introduction systems relied on large diameter wells for liquids addition. Larger diameter wells will usually consist of 6 to 12-inch diameter pipe surrounded by a permeable medium such as stone. In some cases, vertical systems may be constructed by filling around vertical sections and continually adding new sections as waste is deposited. This method cause problems from an opera-

This photo shows a vertical well cluster from the New River bioreactor. Each pipe was originally the same height, but since the wells were constructed to different depths, the amount of settlement that each pipe is exposed to differs. As waste settles, the pipe extended up from the landfill surface. They required a reduction in height periodically. Since an exposed geomembrane was used at this site, maintenance of the well boots was important.

tions perspective, and is therefore not very common.

Small diameter wells have been constructed using open flight rotary augers or hollow stem augers with a diameter varying from 4 to 6 inches. Larger wells are most often installed as single wells at depths nearly the entire length of the landfilled waste.

PVC pipes are commonly used for vertical wells. An advantage to PVC pipes is their ease of installation and maintenance. A major maintenance issue with vertical wells is frequent adjustment of well heights above the surface of landfill. Experience has found that differential settlement of the landfill surface with time resulted in extension of wells above the landfill surface, and that wells should be shortened periodically.

Liquids Addition: Sub-surface Addition System

Horizontal Trenches

In this type of liquid addition system, a large number of horizontal trenches are placed at various levels within the landfill while the waste is placed. Horizontal pipes are embedded in permeable material within the trench. Liquid addition in these lines is generally started after at least one lift of waste has been placed over these trenches. This system is the most common practice as-built bioreactors. HDPE is the most commonly used pipe material due to its strength and durability. Since HDPE pipes require fusion welding, they are often welded together in long lengths outside of the landfill and pulled into place in the trench. Typical perforation size for leachate injection lines is 1/4 to 1/2 inches; with multiple holes every few feet. Typical perforation spacing is two holes every meter. A typical setback distance from the point where the pipe enters the landfill to the point where perforations begin is 100 ft. It is also advised to install a plug or collar of low permeability soil (or similar material) to minimize potential backflow along the non-perforated section of pipe during future operations. The best high permeability filler material used for bedding and cover media would be gravel or rock. For cost considerations, other filler materials like mulch, tire chips or glass may also be used. The advantage of the drainage media is that if the pipe ever breaks, the drainage media can still act as a conduit for liquids movement.

Horizontal trenches were installed in the Polk County bioreactor throughout the progress of waste filling. The primary construction materials included perforated HDPE pipe and several different types of bedding materials. The bedding materials included chipped tires and crushed glass; the material being used in this photo is crushed glass. Horizontal trenches allow the liquids to be introduced into the landfill under the addition of pressure to promote moisture distribution throughout the landfill. Liquids addition only proceeded after sufficient waste surrounded the trench.

At the Polk bioreactor, the locations of the injection lines were identified using common surveying tools as they were constructed. This information was required as part of the reporting process to the regulatory agency and provided the landfill operators with useful information for future landfill activities such as gas well installation.

Infiltration Blankets

This type of system consists of a pipe embedded in a highly permeable media (or material) laid over a much larger area of landfilled waste than a buried trench.

This photo shows a leach bed constructed for adding liquids at the Polk County bioreactor. At this site both shredded tires and crushed glass were used as bedding material. At other sites, manufactured products such geonets have been employed. At the Polk county bioreactor, 1 ft of bedding material was substituted for the daily cover and the new lift of waste was placed directly on top. HDPE pipes were buried in the bed for liquids addition.

Infiltration blankets act as installed layers, typically one to two feet thick of highly permeable materials. Infiltration blankets can be used to provide uniform distribution of recirculated leachate over the widest possible area. This system is constructed as landfilling progresses and can be regarded as buried infiltration pond. Horizontal galleries or granular beds can be installed within lifts of waste to provide large areas for liquids distribution.

Liquids Addition: Seeps

Leachate seeps are a common occurrence at landfills in wet climates and should be expected in landfill that practice liquids addition. Seeps are evidenced by wet spots, typically on the side slopes and at the base of landfill, which exhibit color, odor, and often attract insects. The primary concern with seeps is the potential for off-site leachate migration. Seeps occur because of several factors, and an operator's understanding of the factors can sometimes help prevent and/or control them.

- Waste is heterogeneous. Because waste is not uniform, preferential for liquids flow will develop. Some waste components, such as plastic, film, can intercept liquids and redirect them.

- Waste is more permeable laterally than horizontally. This occurs because of the waste is compacted in layers. Thus it is often easier for moisture to follow sideways rather than straight down.

- Cover materials can greatly impact moisture flow. Cover soils (or ADC) that with low permeability (clay, ash) act as a layer to intercept and route leachate to the side of the landfill. High permeability cover material such as sand can likewise act as preferential path for moisture flow.

Landfill operators practicing liquids addition should expect leachate seeps. Steps should be taken to prevent seeps from occurring and to address them when they do.

Preventive measures include:

- Avoid cover layers with permeabilities on one extreme or the other. If this can't be avoided, scrape or disturb the cover soil as much as possible before placing the new waste lift. This is especially important near the side slopes of the landfill.

- Grade waste deck near the edge of landfill away from side slope. This may be difficult depending on how stormwater is controlled during operation, but any opportunity that reduces leachate flow paths to the side slope will help.

- Work with the design engineer and construction crew to minimize seepage potential with liquids addition system. For subsurface systems where liquids are applied under pressure, avoid pressurized areas close to the slopes. Minimize the number of penetrations into the side slopes. Add seep collars (e.g. clay plugs) to prevent liquid back flow along the pipe, trench or well.

Control measures include:

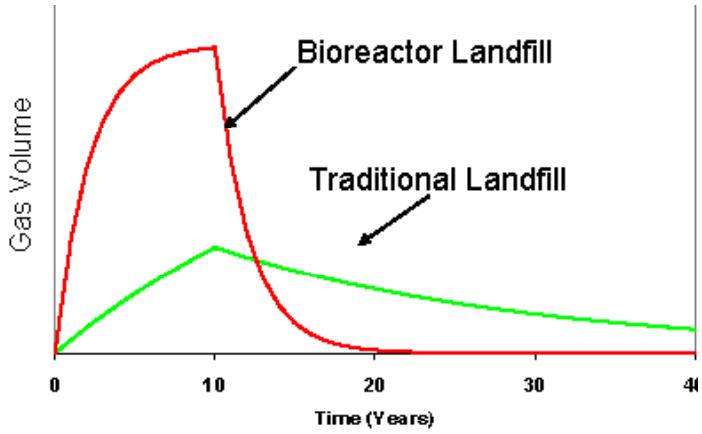
- Work with the design engineer to include a good toe drain system to capture leachate seeps at the landfill toe and to return it to the leachate collection system.

- Routinely inspect for seeps. Record keeping should include noting the location of seeps. Seep locations should be connected with liquids addition to identify operational control strategies.

- Develop and administer a seep management plan. Once a seep is detected, have a procedure in place for fixing and have needed supplies on hand. Common methods to fix include excavating the seep area and routing the leachate back into the waste and compacting clay over the seep area.

At the Polk County bioreactor, perforation in the HDPE injection pipe stopped at least 100 ft from the landfill slope. To minimize the potential for leachate seeping along the pipe, a clay plug was placed in as much of the non-perforated section as possible.

Landfill Gas Extraction: Basics



Gas Generation Rate in Traditional and Bioreactor Landfill

Landfill gas (LFG) is a direct by-product of anaerobic waste decomposition, LFG production is accelerated in anaerobic bioreactor landfills. Gas from anaerobic decomposition of waste is primarily composed of methane (CH_4) and carbon dioxide (CO_2). Typical landfill gas has slightly more CH_4 than CO_2. Other trace components such as water vapor, hydrogen sulfide and a variety of organic chemicals, are also founds in LFG.

The increased gas production may prove beneficial to the landfill operator. The economics of gas conversion to energy at times becomes more feasible when there is greater gas production over a shorter period. If the increased gas production is managed correctly, it has positive implications for energy production and environmental impact. However, if not collected immediately, much of the advantage of energy recovery is lost, and impacts the environment due to uncontrolled release of LFG to the atmosphere. Voluntary use of LFG may also be eligible for carbon credits for the landfill operator.

Different techniques may be used to collect LFG. Possible options include use of horizontal collection systems or vertical wells. A blower system is used to induce a vacuum in the gas manifold and the wells or trenches and to extract gas from the landfill interior. The vacuum has to be maintained in such a way so as not to draw air into the landfill, as the air drawn into the landfill may slow down the methanogenic microbial activity and can alos result in landfill fires.

For bioreactor landfill, the design engineer should take into account the faster gas production rate. Leachate recirculation in bioreactor landfill poses special challenges in designing landfill gas collection system. Accelerated gas production at wet landfills also results in several additional challenges for bioreactor operators. Based on these challenges, suitable gas collection strategies must be adopted.

Landfill Gas Extraction: Issues and Strategies

Increased Atmospheric Emissions: Generally, leachate recirculation and other forms of liquid addition are practiced during the operational years of the landfill. Leachate production is greatest during this period and it is the only time when certain types of liquid addition system may be utilized (e.g., direct application to the working face using tankers or spray system). The operating years of a landfill cell's life are also the time when gas collection efficiency may be at its lowest. Thus, bioreactor landfill operators must control and collect gas sooner than conventional landfills, or else atmospheric emissions will be increased. In addition to regulatory problems and general environmental concerns, this cause operational issues because of odor.

Increased Gas Collection Capacity: The capacity of the gas collection and conveyance system will need to be greater than a similar size conventional landfill (e.g., larger pipe diameter). Since many bioreactor landfill operators will practice liquids addition during the operational life of the landfill prior to closure, the approach for gas collection may need to be different than typical vertical well extraction systems at conventional landfills. The additional amount of condensate should also be considered in the design.

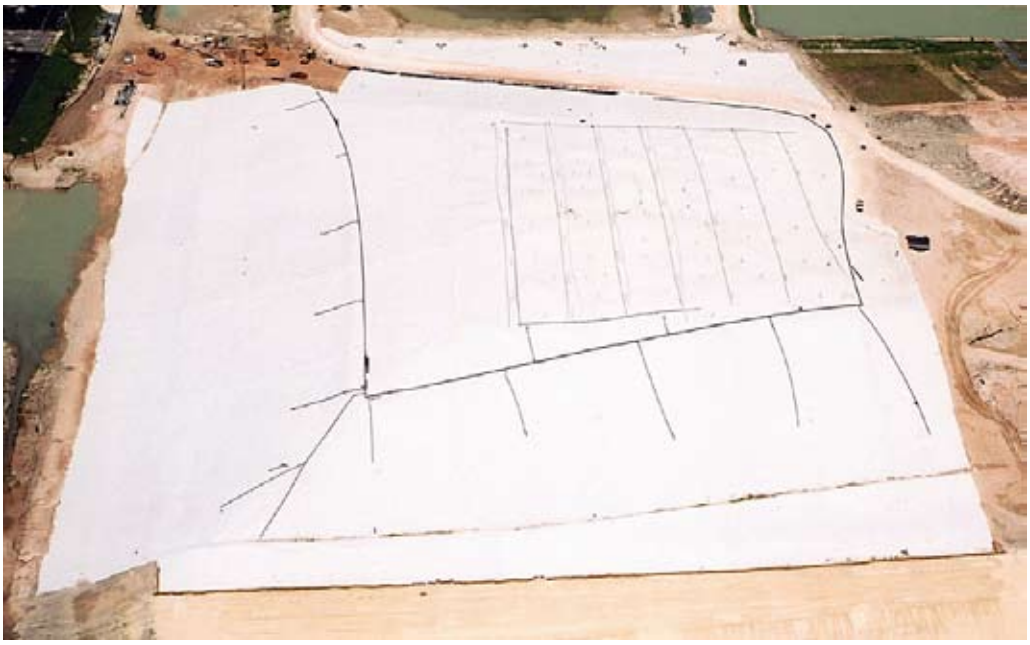
Liquids in Gas Collection Lines: The difficultly with traditional gas collection devices at bioreactor landfills is that they tend to fill with liquids. Liquid and gas inside a landfill will follow the path of least resistance. If a gas collection device intercepts part of a saturated zone, liquids from this zone can migrate into the device. This problem has been observed for both vertical wells and horizontal trenches. The presence of moisture greatly reduces the ability of gas to move through the waste. If the waste surrounding a gas collection device is flooded, even if large amounts of gas are produced, gas will move elsewhere to a path wit less resistance.

This photo show the construction of gas trenches on the side slope of New River Regional Landfill.

Strategies

To face the challenges posed by gas collection in wet landfills, bioreactor landfill operators may need to employ different strategies than conventional landfill.

Methods of Gas Collection by Different Strategies	
Dewatering Pumps	Special dewatering pumps are available that can be added to gas extraction devices to remove the liquids. These are often used at landfills in wet climates that do not practice liquids addtion.
Leachate Recirculation Devices for Gas Extraction	Newer horizontal leachate injection lines can be used for gas collection. Experience has found that once liquids are added to a trench in large amounts, gas collection becomes difficult.
Leachate Collection System	Gas may be collected from the leachate collection system, Path of least resistance, gas produced in the bottom of the landfill will migrate downward. Many landfills have successfully incorporated gas collection from the leachate collection system.
Surface Caps	Horizontal trenches on the surface of the waste but under the exposed geomembrane cap (EGC) may be used for gas collection. A toe drain should be installed around the perimeter of the landfill to intercept seeps underneath the EGC and to route the liquids to leachate collection system.



The New River bioreactor was constructed with an exposed geomembrane cap. This proved to be a good method to contain side slope seeps. It also became an integral part of the gas collection system.

Air Addition: Basics

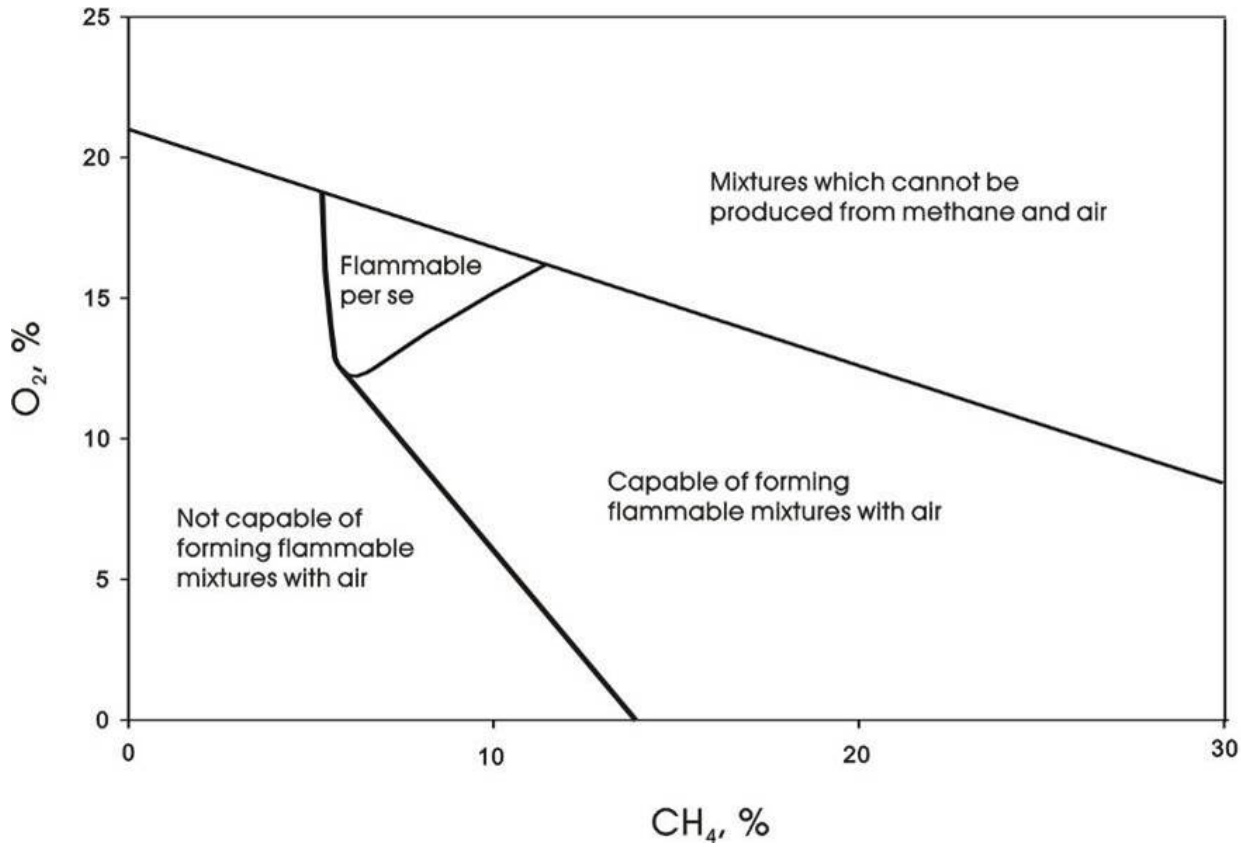
Some solid waste professionals have proposed air addition (in addition to liquids addition) for the purpose of achieving rapid waste stabilization. The aerobic conditions created in the landfill by the addition of air can stabilize waste more rapidly than anaerobic systems. The aeration of landfills is similar in concept to operate MSW compost plants. The aerobic process results in greater heat production and can thus lead to an increase in landfill temperature (above that seen in typical anaerobic landfills).

For aerobic bioreactors, the balance of air and water is critical. Sufficient water must be available to provide a suitable environment for the microorganisms. If sufficient water is not available, excessive heat production can result in the combustion of the waste. If water is available in excess, air cannot reach the waste due to the physical barrier created by the water and the system will not run aerobically. Air addition has been proposed for warming up cold landfills and preparing them for anaerobic bioreactor treatment. In practice, it may be impossible to have a completely aerobic landfill, because waste in deeper sections of the landfill is dense and well compacted, and thus air permeability is very low. In truly aerobic landfills, methane will not be produced. This eliminates potential benefits of methane production for energy. Laboratory experiments suggest that aerobic bioreactor landfills will have lower leachate strength in comparison to anaerobic bioreactors.

The New River bioreactor was equipped with air blowers so air could be added to some of the vertical wells. The objective was to study aerobic bioreactor operation in part of the landfill unit. The air addition system was never utilized to the extent originally design because of difficulties in adding air to deep sections of the landfill, to wet areas of the landfill, and because of the difficulty in controlling temperature. The operators monitored temperature to minimize the potential for a landfill fire.

Are fires and explosions a concern at aerobic bioreactors?

Aerobic waste degradation results in the release of more heat than anaerobic activity. Release of rapid heat can increase the waste temperature and can result in possible landfill fires. this must be controlled by careful monitoring of temperature and having the ability to add water if needed. The flammability range for methane is between 5% and 15% but this only refers to the flammability of methane with air. When nitrogen and other gases are present, this range is decreased. The figure shows the flammability chart with percent oxygen versus percent methane. The explosive range is indicated.



Air Addition: System Configuration

For aerobic bioreactors landfills, air addition is another important consideration apart from uniform addition of moisture in the landfill. For a typical air addition system, three components are needed: a blower; a conveyance mechanism to deliver air from the blower to the landfill unit; a scheme to distribute air to the landfilled waste mass commonly termed as air addition system. Unlike liquids, air can only be delivered through a piping network to the points of interest. The blowers are selected based on the volume of air, flow rate, and pressures that are to be maintained.

Air addition rates are not standardized. Air addition rates may require field determination of achievable rates, pressure, and gas quality and temperature measurements. Air addition rates can be estimated based on following factors.

- waste composition estimates,
- aerobic waste decomposition
- operational objectives

The design engineer will suggest the air addition rates depending on the above mentioned factors. Generally, achievable air addition rates range between 10 to 40 scfm at pressures up to 10 psi.

Several factors influence the air addition system's effectiveness. Due to heterogeneous nature of the solid waste placed in the landfill, the wide variation in the capability of the waste to transmit air is expected. Another consideration is presence of higher moisture contents in the landfilled waste; moisture acts as a physical barrier to air flow and can reduce the flow significantly. Fire formation due to excessive temperature is another concern and the presence of liquids in appropriate quantities is of great importance. Balance between having sufficient moisture to prevent the occurrence of fires and to not reduce airflow remains a challenge.

The design of an air addition system includes estimation of the volume of air that is needed to be added (or extracted in case of induced system), selection of type of air addition system (vertical wells or horizontal lines), detailed specifications on sizing and configuration of the air addition devices, spacing between individual devices, and selection of materials. Various design elements of an air addition system are listed and briefly described in the Table on next page.

Bioreactor Landfill Monitoring

Monitoring is an important aspect of all landfill operations. The parameters that must be measured, along with the testing frequency and reporting requirement, will be spelled out in the sites regulatory permit. Monitoring is even more critical for landfills operated as bioreactors because of the additional liquids and gas involved. Some additional monitoring may be required by the permitting authority to ensure safe operation. Other monitoring may be designed by the landfill operator to support control and performance of the waste treatment system.

Typical Monitoring Categories

* Leachate Characteristics
* Liquid Volume
* Liquid Head on Liner
* Landfill Gas Quality
* Landfill Gas Volumes
* Gas Emissions
* Waste Characteristics
* Landfill Settlement
* In-situ Instrumentation

Monitoring and proper recordkeeping is important at all landfills, but it is especially critical at bioreactor landfills. Most bioreactor landfills have operators who are responsible for routine data collection and reporting. Keeping track of the liquid balance, both liquids added to the landfill and leachate removed from the landfill should be a major emphasis.

Multiple different monitoring parameters may be used. No one parameter will provide the operator all they need to know, so a combined set of results are evaluated. Common monitoring parameters are described below. For additional guidance, consult "Monitoring Approaches for Landfill Bioreactors" by the US EPA.

The staff responsible for daily bioreactor operation will have multiple responsibilities and should be properly trained. Responsibilities will include operation of the liquids addition system, inspection of the landfill site, and recording of necessary data. In many cases these operators will also play a large role in managing the gas collection system. It is also critical that operators carefully monitor and maintain components of the fluid handling system such as pumps and meters. Proper prevention maintenance is important because the ability manage liquids is such a major component of bioreactor operations.

Liquids Balance. Because of the critical role of moisture in bioreactors, the volume of liquids added and removed from the landfill should be tracked closely. Wherever possible, liquid volume data should be recorded for specific locations, such as the amount of liquid recirculated to a given trench or well or the amount of leachate produced by a designated area of the landfill. This information will provide guidance on whether targets are being met, which areas have been wetted to the greatest extent, and whether leachate is being absorbed by the waste or just circulating through the landfill. To complete the water balance, meteorological information such as rainfall should be tracked.

Some landfill operators find it very useful to monitor liquid levels within the landfill system. Periodic measurement of liquid levels in sumps and wet wells can provide information on the performance of the leachate drainage and collection system. Some regulatory agencies require measurement of leachate head on the liner. Simple sump measurements typically do not provide a good method of measuring head on the liner. Other techniques, such as instruments on the liner and piezometers, are most commonly used when such measurements are required.

Leachate Quality. The chemical quality of leachate provides the operator a means to assess conditions occurring within the landfill. Measurement of dissolved solids content or chemicals such as chloride can provide an indication of the direct contribution of stormwater to leachate. Parameters such as biochemical oxygen demand (BOD) and chemical oxygen demand (COD) can be used to assess where the landfill is with respect to waste decomposition. Leachate with BOD:COD near 1.0 is indicative of fresh waste early in the stages of decomposition, whereas a value in 0.1 or less is usually thought to represent more stable waste areas.

Leachate Monitoring Parameters (Adapted from Tolaymet et al. 2004 [3])	
Parameter Category	**Parameter**
Primary Leachate Monitoring Parameters (Monthly)	Temperature pH Conductance Total Dissolved Solids Alkalinity Chloride Bromide Floride Sulfate Chemical Oxygen Demand Biochemical Oxygen Demand Total Organic Carbon Total Phosphorous Ortho Phosphate Ammonia Nitrite Nitrate
Secondary Leachate Monitoring Parameters (Quarterly)	Volatile Organic Compounds (VOCs) Semi-Volatile Organic Compounds (SVOCs) Volatile Fatty Acids Metals and Ions (Arsenic, Barium, Cadmium, Calcium, Copper, Chromium, Iron, Lead, Magnesium, Mercury, Potassium, Sodium, Selenium, Silver and Zinc)

Operators should realize, however, that leachate quality alone does not characterize the entire landfill. In many cases, leachate quality measured from the leachate collection system is only representative of waste from lower parts of the landfill. It is very possible that a landfill with very "stable" leachate could contain a large fraction of leachate from undegraded waste. Leachate quality provides insight, but alone cannot characterize the landfill.

Landfill Gas. Since the end product of anaerobic waste decomposition is landfill gas, monitoring gas is appropriate. Landfill gas is comprised primarily of methane (CH4) and carbon dioxide (CO2). The relative composition should not be noticeably different if it is a bioreactor or not. Thus while gas monitoring is critical to assess the efficiency of a gas collection, it does not provide indication of the state of waste stabilization.

The gas production rate for a bioreactor landfill is expected to be greater than a traditional landfill. This monitoring gas production may provide useful information on bioreactor activity. The utility of gas flow data depends on the efficiency of gas collection. Bioreactor landfills with efficient gas collection system should see more gas than dry landfills. Caution should be used, however, as it is plausible that a gas well may not demonstrate high gas flow rates, not because waste is stabilized, but simply because the well is flooded with leachate. As is the case with leachate gas measure-

ment are a critical component of landfill operation, but caution should be used when interpreting the data.

Settlement. As waste decomposes, gas is formed, and the volume of the landfill decreases (the waste surface settles). Settlement is valuable to track because it correlate to additional disposal capacity. Like leachate and gas, settlement provides useful information on the performance of the bioreactor, but does not provide complete characterization of the waste in the landfill.

In-Situ Measurements: Several different types of instruments have been proposed for measuring properties inside bioreactor landfills. For the most part, this has been part of research-oriented landfill sites. Pressure transducers of various configurations can be used to measure liquid head on the liner or within the waste. Previous trials have been met with mixed results. In-situ temperature measurements have been conducted with success. In-situ moisture measurements also has had some success with respect to determining whether a landfill area has been impacted by liquids addition. The difficulties of using in-situ instrumentation include cost, potential instrument failure, and installation. When wires are routed out of the landfill to bring the signal to a measurement device, this creates a potential pathway for moisture movement. In summary, instruments may have benefits for particular application or for addressing specific unknowns, but routine use is in most cases not needed for successful bioreactor operation.

Moisture sensors were buried in the New River bioreactor. The sensor in the photograph is a resistance-based sensor. The sensors were successful in responding to conditions when added liquids reached the area where the sensor was located. However, the sensors did not provide an accurate estimate of the magnitude of the moisture content. At the end of the experiment, nearly all of the sensors in the New River bioreactor gave readings indicated that they were wet. One limitation to use of in-situ sensors such as these are preferential moisture flow along the path created by the installation borehole was the wires are located.

Waste Properties: While leachate and gas characteristics provide an indication of what is happening to the waste in a landfill, they are indirect measures of waste properties. One approach to assessing waste characteristics is to collect a sample of waste and perform appropriate analysis.

This is accomplished by drilling a hole into the land-

fill and retrieving the waste. Several different parameters are often tested on excavated waste samples, including moisture content, volatile solids, methane yield, and cellulose/lignin content. Waste sampling and characterization gives the operator the most accurate means to assess the condition of their waste. The disadvantage of this approach is that it is costly and it may be difficult to characterize enough samples to be truly representative. For normal bioreactor landfill operations, solids sampling is normally any advised at points in a project when demonstration of stability is appropriate or when performance of the system is in question.

Some waste professionals have proposed that once a bioreactor landfill has been sufficiently stabilized, the waste may be "reclaimed" or "mined" to recover usable soil/compost and airspace for additional waste disposal. This photo shows a landfill mining operation at a landfill in California (not a bioreactor). Excavated waste is screened to separate waste items that must be disposed from fine materials that may be reused. The reuse of screened soil outside the landfill will depend on chemical quality and regulatory requirements.

Long Term Considerations for Bioreactors: Full-scale application of bioreactor technology suggests that relatively complete stabilization of waste once wetted can be reached within 5 to 10 years. With this stabilization should come additional disposal capacity. This disposal capacity will only be available if the landfill is operated in a manner where the capacity occurs in a viable disposal (e.g., if the landfill area was closed and capped, it would not be attractive for additional filling). Some operators are exploring the idea of using temporary geomembrane caps that can be economically removed to allow more waste disposal.

While operating a landfill as a bioreactor, it does not increase the total amount of gas produced, however, the gas is produced much more quickly. For some sites, this means that gas extraction and energy conversion infrastructure will not be needed as long and can be potentially be used at other sites. For sites which continue to landfill as a bioreactor, gas production will continue at an approximately steady state corresponding to incoming waste rates.

At some point, continued liquids addition into treated waste is no longer necessary. Leachate will still be produced from those areas to some extent and must be managed appropriately. If bioreactor landfilling continues at the same site, this mature leachate can be used as a source of moisture for new landfill areas. If landfilling has stopped at the site, some form of leachate treatment will be needed. Since most of the organic strength of the leachate is gone, treatment technologies that work well with mature leachate should be used.

Some bioreactor have suggested that once the waste is adequately stabilized, the landfill can be mined. Using this approach, often can adequate post-treatment of curing and drying. The landfill will be excavated. Soil and compost will be separated out for future use and the stabilized residuals will be permanently landfilled in another unit. This would then allow new waste to be added and treated in the original bioreactor landfill unit.

Glossary and Abbreviations

Aerobic: A life or process that require, or are not destroyed by, the presence of oxygen.

Anaerobic: A life or process that occurs in, or is not destroyed by, the absence of oxygen.

Biochemical Methane Potential (BMP): An assay of the biodegradability of materials under anaerobic conditions using methane production.

Biochemical Oxygen Demand (BOD): A measure of the amount of oxygen consumed in the biological processes that break down organic matter in water.

Biodegradable: Capable of decomposing biologically under natural conditions

Carbon Dioxide (CO_2): Important climate changes gas that is the end product of cellular respiration. Produced in both aerobic and anaerobic environments.

Carbon Monoxide (CO): A colorless, odorless, poisonous gas produced by incomplete fossil fuel combustion.

Cellulose to Lignin Ratio: An analytical measurement that measures available cellulose and lignin in the waste mass. Generally cellulose is degradable to methane while lignin is not. The end result is that over time in a treated landfill the cellulose goes away.

Cellulose: an organic compound with the formula $C_6H_{10}O_5$. Paper contains cellulose.

Chemical Oxygen Demand (COD): A measure of the oxygen required to oxidize all compounds, both organic and inorganic, in water.

Code of Federal Regulations (CFR): A document that codifies all rules of the executive departments and agencies of the federal government. It is divided into fifty volumes, known as titles. Title 40 of the CFR (referenced as 40 CFR) lists all environmental regulations.

Compost: A humus or soil-like material created from aerobic, microbial decomposition of organic materials such as food scraps, yard trimmings and manure.

Dissolved Oxygen (DO): The amount of oxygen dissolved in water. Unit is part per million or mg/L.

Electrical Conductivity: A measure of the liquid's ability to conduct electricity, and therefore a measure of the liquid's ionic activity and content (typically measured in micromhos). The higher the conductivity, higher is the concentration of ionic (dissolved) constituents.

FDEP: Florida Department of Environment Protection.

Flow Rate: Mass or volume flow through unit area per unit time.

Flowmeter: A device to measure flow rate.

Global Warming: Phenomenon that the average measured temperature of the Earth's near-surface air and oceans increases since the mid-twentieth century.

Heavy Metals: The metallic elements with high atomic weights; (e.g. mercury, chromium, cadmium, arsenic, and lead); can damage living things at low concentrations and tend to accumulate in the food chain.

Human Health Risk: The likelihood that a given exposure or series of exposures may have damaged or will damage the health of individuals.

Hydrogen Sulfide (H_2S): A gaseous toxicant likely forming during anaerobic decomposition with sulphur compounds. .

Hydrology: A science dealing with the properties, distribution, and circulation of water.

Irrigation: Applying water or wastewater to land areas to supply the water and nutrient needs of plants.

Leachate Collection System: A system that gathers leachate and pumps it to the surface for treatment.

Leachate: Liquid that leached out from landfilled wastes.

Lignin: A substance that, together with cellulose, forms the woody cell walls of plants and the connective material between them. Lignin is resistant to decomposition.

Liner: A relatively impermeable barrier designed to prevent leachate migration through a landfill bottom. Liner materials include synthetic and earth materials.

Lower Explosive Limit (LEL): The concentration of a compound in air below which the mixture will not catch on fire.

Methane: A colorless, nonpoisonous, flammable gas created by anaerobic decomposition of organic compounds. A major component of natural gas used in the home.

Moisture Content: The amount of water in a solid material, such as soil and waste. It can be expressed as the weight per unit of dry soil (waste) or as the volume of water per unit bulk volume of the soil (waste).

Municipal Solid Waste: Common garbage or trash generated by industries, businesses, institutions, and homes.

Nitrogen Oxides (NOx): Gaseous compounds composed of nitrogen and oxygen. A major component of photochemical smog.

Nutrient: Any substance assimilated by living things that promotes growth. The term is generally applied to nitrogen and phosphorus in wastewater, but is also applied to other essential and trace elements.

Oxidation-Reduction Potential: The electric potential required to transfer electrons from one compound or element (the oxidant) to another compound (the reductant); used as a qualitative measure of the state of oxidation in water treatment systems.

Parts Per Billion (ppb)/Parts Per Million (ppm): Units commonly used to express contamina-

tion ratios, as in establishing the maximum permissible amount of a contaminant in water, land, or air.

Permeability: The rate at which liquids pass through porous media in a specified direction.

Permit: An authorization, license, or equivalent control document issued by EPA or an approved state agency to implement the requirements of an environmental regulation; e.g. a permit to operate a wastewater treatment plant or to operate a facility that may generate harmful emissions.

pH: An expression of the intensity of the basic or acid condition of a liquid; may range from 0 to 14, where 0 is the most acid and 7 is neutral. Natural waters usually have a pH between 6.5 and 8.5.

Post-Closure: The time period following the shutdown of a waste management or manufacturing facility for monitoring purposes.

Retrofit: Addition of a pollution control device on an existing facility without making major changes to the generating plant. Also called backfit.

Run-Off: That part of precipitation, snow melt, or irrigation water that runs off the land into streams or other surface-water. It can carry pollutants from the air and land into receiving waters.

Sanitary Landfills: Disposal sites for non-hazardous solid wastes spread in layers, compacted to the smallest practical volume, and covered by material applied at the end of each operating day.

Saturation: The condition of a liquid when it has taken into solution the maximum possible quantity of a given substance at a given temperature and pressure.

Solid Waste Disposal: The final placement of refuse that is not salvaged or recycled.

Solid Waste Management: Supervised handling of waste materials from their source through recovery processes to disposal.

Stabilization: Conversion of the active organic matter into inert, harmless material.

Standards: Norms that impose limits on the amount of pollutants or emissions produced. EPA establishes minimum standards, but states are allowed to be stricter.

SWANA: Solid Waste Association of Nrth America.

Total Dissolved Solids (TDS): All material that passes the standard glass river filter; now called total filtrable residue. Term is used to reflect salinity.

Total Kjeldahl Nitrogen (TKN): Sum of organic nitrogen and ammonia in a leachate and is measured in milligrams per liter (mg/L).

Total Organic Carbon (TOC): The total organic carbon present in a liquid sample and is often used as a non-specific indicator of leachate quality. Total organic carbon is a more convenient and direct expression of total organic content than either BOD or COD, but does not provide

same kind of information.

Total Suspended Solids (TSS): A measure of the suspended solids in wastewater, effluent, or water bodies, determined by tests for "total suspended non-filterable solids."

Transpiration: The process by which water vapor is lost to the atmosphere from living plants. The term can also be applied to the quantity of water thus dissipated.

Treatment Plant: A structure built to treat wastewater before discharging it into the environment.

USEPA: United States Environment Protection Agency.

Volatile Fatty Acids (VFAs): A group of compounds that include acetic acid (the lowest molecular weight VFA), propionic acid, isobutyric acid, butyric acid, isovaleric acid, valeric acid, hexanoic acid and other higher molecular weight (MW) compounds.

Volatile Organic Compound (VOC): Any organic compound that participates in atmospheric photochemical reactions except those designated by EPA as having negligible photochemical reactivity.

Volatile Solids: Those solids in water or other liquids that are lost on ignition of the dry solids at 550° centigrade.

(Adopted from [4])

Resources and References

Internet Resources

- Hinkley Center for Solid and Hazardous Waste Management, www.bioreactor.org
- EPA bioreactor: website www.epa.gov/garbage/landfill/bioreactors.htm
- ITRC website: www.itrcweb.org/gd_ALT.asp
- The Interstate Technology & Regulatory Council (ITRC), Alternative Landfill Technologies Team, (2006). Characterization, design, construction, and monitoring of bioreactor landfills. Technical/ Regulatory Report

Training Courses

- SWANA provides a bioreactor landfill certification program. http://www.swana.org/www/EDUCATE/Certification/BioreactorLandfill/tabid/96/Default.aspx.

Technical Literature Cited

[1] Gurijala, K.R. and Suflita, J.M. (1993). "Environmental factors influencing methanogenesis from refuse in landfill samples." Environmental Science and Technology, 27(6), 1176-1181.

[2] Reinhart, D. R., and Townsend, T. G. (1997). Landfill bioreactor design and operation. Lewis Publishers, Boca Raton, FL, USA.

[3] Tolaymat, T. Kremer, F., Carson, D., Davis-Hoover, W. (2004). Monitoring Approaches for Landfill bioreactors. U.S. EPA, Cincinnati, OH, EPA/600/R-04/301

[4] USEPA web site http://www.epa.gov/OCEPAterms/aterms.html Assessed March 1, 2008

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