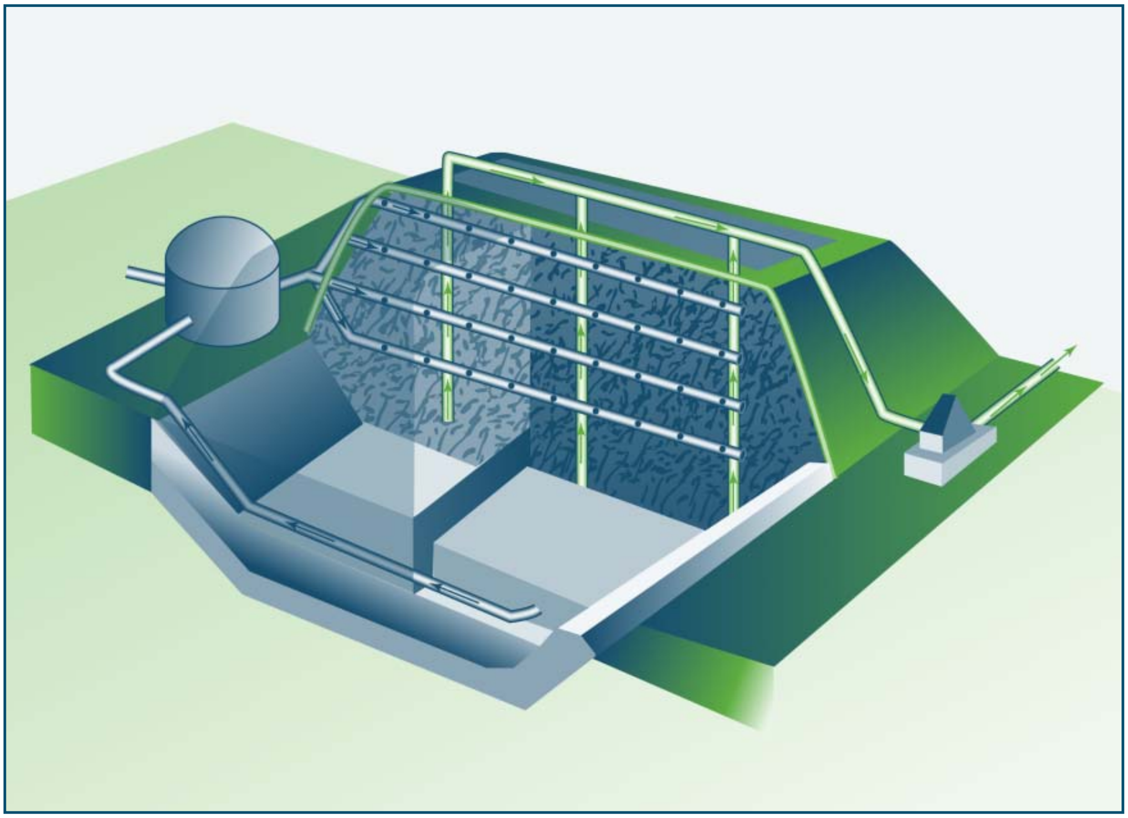
Technical/Regulatory Guideline

Characterization, Design, Construction, and Monitoring of Bioreactor Landfills



February 2006

Prepared by
The Interstate Technology & Regulatory Council
Alternative Landfill Technologies Team

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The team members depend on input from all perspectives to give ITRC documents the broadest practical application in the industry since the team members have displayed that a mix of perspectives and skills are necessary to further understanding of bioreactor landfills. The team also wishes to recognize the efforts of the researchers investigating these technologies and the consultants and businesses striving to deploy these new technologies. These include Waste Management Incorporated, Alan Environmental LLC, GeoSyntec Consultants, University of Missouri, Air Force Center for Environmental Excellence, Department of Defense-Navy, Department of Defense, Lackland Air Force Base, Unites States Department of Agriculture, AquAeTer, Inc, Aquaterra Environmental Solutions, Inc, U.S. Environmental Protection Agency, Region 5, and the USEPA Office of Air Pollution. The states represented above contributed the latest research, years of experience, and the case study information contained in this document.

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EXECUTIVE SUMMARY

This Bioreactors Landfill Technical/Regulatory Guidance Document is primarily written for decision makers associated with the plan development, review, and implementation of bioreactor landfills. The decision makers include, at a minimum, regulators, owners/operators, and consultants. This document focuses on the decisions and facilitating the decision processes related to design, evaluation, construction, and monitoring associated with bioreactor landfills.

To facilitate the use of this document and understanding of the decision process, a decision tree is provided in Chapter One (1.0). In the electronic version of this document, clicking on any process box or decision diamond in the decision tree accompanied by a section number will take the reader to that place in the document.

Bioreactor landfills are designed and operated by increasing the moisture content of waste to enhance the degradation and stabilization of the waste material. The team believes that available research indicates that municipal solid waste degraded in a bioreactor landfill may reduce the long term threat potential relative to a dry tomb landfill resulting from breakdown of organics and the possible sequestration of inorganics. Specifically, bioreactor landfills may accept non-hazardous liquids and sludges to provide nutrients, enzymes, moisture, and bacteria to accelerate biodegradation of both Municipal Solid Waste (MSW) and biosolids. Also, while recirculating leachate from a landfill is fundamental to bioreactor operation, make-up liquids provide additional moisture when not enough leachate is generated from the landfill to attain optimal waste moisture content.

Leachate and make-up liquids recirculation will be collectively referred to as “liquids recirculation” throughout this document. Liquids recirculation accelerates the decomposition of MSW by distributing moisture, nutrients, enzymes, and bacteria throughout the waste mass more efficiently than natural infiltration alone. In addition, various application systems are used to provide a thorough and more homogeneous distribution of moisture throughout the waste material. Liquids recirculation may be accompanied by pressurized air to enhance the aerobic biodegradation process; however, with or without aeration, the anaerobic bioreactor process accelerates gas generation that can offer a revenue stream and decrease the contaminant load in the leachate.

The team believes that bioreactors can expedite beneficial reuse of landfill capacity, resources, and expedited reuse of the property. Because most landfills have little ability to complete the degradation process while in a dry tomb state, landfills of this design continue to be managed as such ad infinitum unless a demonstration can be made that the waste is not longer able to leach undesirable constituent into the groundwater. Bioreactors, on the other hand, design degradation into the landfill, thereby accelerating what will eventually occur, but under controlled and predictable conditions. Planning post closure land use into a landfill is now a reality and there are more choices for land use that would never have been considered when using a dry tomb landfill design. Additionally, landfill capacity can be increased since during degradation waste, volume decreases thereby providing additional landfill space in existing landfill sites.

The team does offer caution because bioreactor landfills must be carefully designed and operated. Many smaller county and local landfills should not consider using bioreactors until they have appropriate scientific and engineering staff to design, monitor, and operate the bioreactor appropriately.

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1.0 BIOREACTORS

Currently the municipal solid waste (MSW) industry is undergoing a transformation in the way waste is managed. Traditionally landfills were constructed to become waste repositories where the waste is entombed, the site fenced off, the grass mowed, and occasionally someone will come for routine monitoring and/or maintenance activities (e.g. sample the groundwater).

Today there is a growing trend to integrate post-closure functional use (see ITRC ALT-4, 2006 in progress) into landfill design, construction, operation, and closure. The process should consider landfill economics with the long-term growth and land-use plans of the community. This practice is to some degree, predicated on the potential threats to human health and the environment associated with the closed landfill's waste materials. Reducing the threats associated with the closed landfills would be the result if the material within the landfill were stable and thereby has a reduced potential to release toxic constituents into the environment. One potential means to achieve waste stabilization and reduced release potential may be by operating the landfill as a bioreactor instead of as a dry waste isolation cell. Bioreactors can degrade and/or sequester the waste material and its associated constituents to the point where the leachate does not contain toxic constituents above applicable drinking water or groundwater standards. Section 1.3 highlights several advantages of bioreactors.

The ITRC ALT team believes that bioreactors can expedite beneficial reuse of landfill capacity, resources, and expedited reuse of the property. This guidance document is intended for use by regulatory agencies, stakeholders, consultants, and industry to assist in permitting, operating, and monitoring a bioreactor landfill. Bioreactor landfills are designed and operated to attain increased waste moisture content to enhance the biodegradation and stabilization of the waste material. Bioreactor landfills also may accept non-hazardous liquids and sludges to provide nutrients, enzymes, moisture, and bacteria to accelerate decomposition of both municipal solid waste and biosolids. Recirculating the leachate generated from the landfill is a primary and fundamental attribute of bioreactor operations. Since make-up liquids may also be used to augment on-site leachate, leachate recirculation and make-up liquids addition will be collectively referred to as "liquids recirculation" throughout this document. Liquids recirculation accelerates the decomposition of MSW by distributing moisture, nutrients, enzymes, and bacteria throughout the waste mass more efficiently than natural infiltration alone. In certain cases, liquids recirculation is accompanied by injected air to enhance the biodegradation process. The bioreactor accelerated waste degradation process enhances gas generation that can provide a revenue stream to the operator and decrease the contaminant load in the leachate. Both of these bioreactor attributes reduce potential threats associated with the landfill, while increasing long-term stability of the waste material.

This guidance intends to help solid waste professionals consider the future picture when evaluating post-closure uses, in addition to addressing the technical details that achieve successful results. The team members challenge all those involved in landfill decision making process—owners and operators, consultants, government officials, and the public—to keep an open mind, to see symbiotic relationships, and to seize opportunities for meaningful post-closure use of landfill sites where technically feasible, economically viable, and supported by the community.

All landfills are under intense and continuous public and regulatory scrutiny. Alternative landfill technologies such as liquids recirculation are often viewed skeptically by landfill critics. As such, it is essential that systems be carefully designed, constructed, and operated. Even a single failure caused by an inadequate recirculation system could have negative and far-reaching ramifications. Proper design, construction, and operational practices will facilitate the successful implementation of innovative technologies such as bioreactors. To approach a bioreactor decision, there are intuitive steps best followed to ensure regulatory and technical questions are addressed before a commitment is made to the use of a bioreactor. Figure 1-1 presents the team’s suggested series of questions. Each question is discussed in more detail in the section identified in each shape.

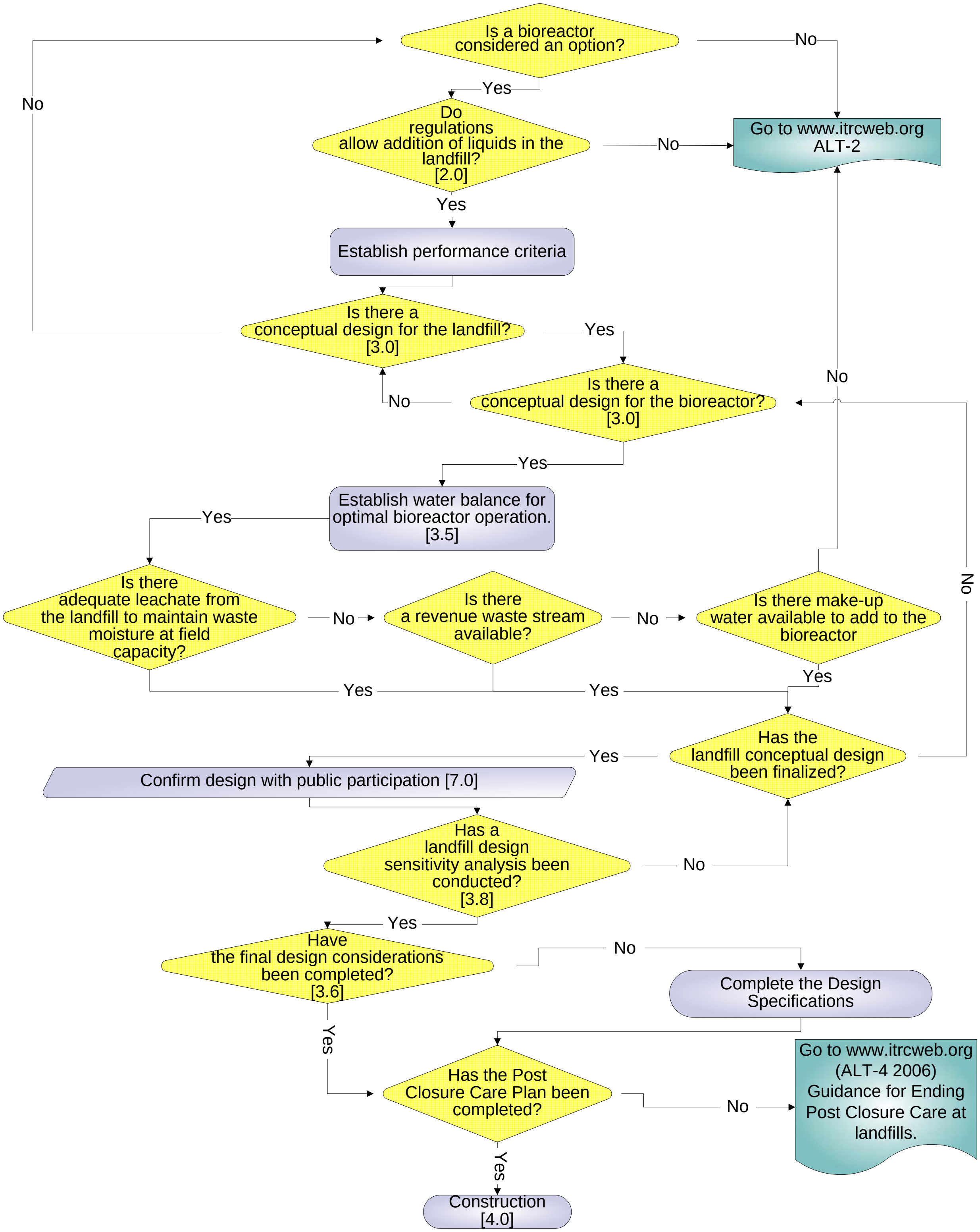


Figure 1-1. Bioreactor Decision Tree

Like most operations, bioreactor performance can be influenced by subtle and unseen circumstances. Bioreactors are closed vessels and visual inspections are difficult to perform. While monitoring the performance of a bioreactor, adjustments that will enhance or optimize the bioreactor landfill performance can be made. This could mean more rapid degradation and thereby a shorter timeframe for stabilization. To take full advantage of the bioreactor, these adjustments might require features of the landfill to be redesigned. Whatever the nature of the adjustment, operators should carefully monitor their operation during startup. Figure 1-2 shows a typical interactive approach for a bioreactor startup. The experience gained from early operations offers the operator the opportunity to learn particular effects that changes in design have on the optimal operations of a bioreactor.

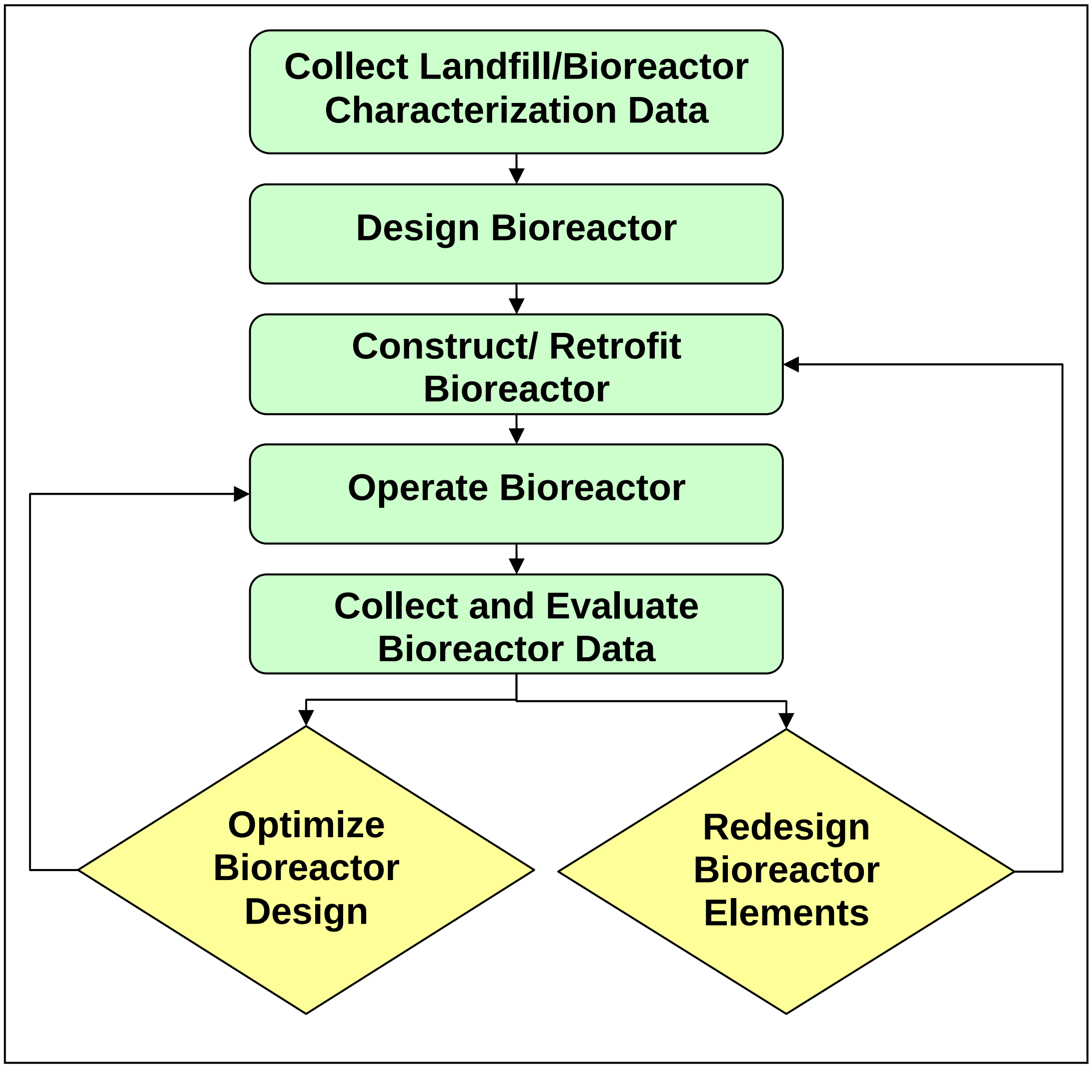


Figure 1-2. The interactive startup or learning bioreactor flow diagram

1.1 Background of Bioreactor Concepts

1.1.1 Definitions of Bioreactors

Research and practice have resulted in several different definitions of bioreactors. Some of the names and definitions are presented below. However, the team has chosen to use the EPA's Office of Research and Development's definition of a bioreactor as follows:

> "Bioreactors are landfills where controlled addition of non-hazardous liquid wastes or water accelerates the decomposition of waste and landfill gas generation."

While this is a general description of a bioreactor, it is beneficial to be more inclusive than exclusive, which will allow greater flexibility in the design and operation of a bioreactor. This could prove especially useful if a bioreactor changes operating practices or functions throughout its life cycle.

Previous investigations or studies have defined bioreactor landfills as follows:

Dr. Fred Pohland, (Recognized as the first to publish bench scale results of liquids recirculation in the 1970s) University of Pittsburgh, Hazardous Waste Research Center

- Suggests that a landfill that adds nutrients, buffers, or inoculum in addition to recirculating landfill leachate to achieve a moisture content of 40-60% (by weight) is a bioreactor landfill

EPA's Office of Research and Development proposed the following definition:

- **"**A landfill designed and operated in a controlled manner with the express purpose of accelerating the degradation of MSW inside a landfill containment system."

Solid Waste Association of North America (SWANA) Definition

- 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 biostabilization of waste."

USEPA MACT Rule

- "Any landfill or portion of a landfill where liquid other than leachate is added in a controlled fashion into the waste mass (often in combination with recirculation of leachate) to reach a minimum of 40% by weight."
- Requires installation of gas control and collection system prior to liquid addition
- Operate gas control within 180 days after achieving moisture of 40%.
- Bioreactor is closed, liquid addition ceased for one year or more
- Can remove or stop control when EG/NSPS (Emission Guidelines/New Source Performance Standards) are met

The general types of bioreactor landfills include but are not limited to:

- **Aerobic** - In an aerobic bioreactor landfill, leachate is removed and re-circulated, often with additional water, into the landfill in a controlled manner. Air is simultaneously injected into the waste mass, using vertical or horizontal wells, to promote aerobic bacterial activity and accelerate waste degradation.

- **Anaerobic** - In an anaerobic bioreactor landfill, moisture is added to the waste mass in the form of re-circulated leachate and other water to obtain optimal moisture levels. No additional air is added to the landfill, since the intent is to promote an anaerobic environment. Biodegradation, by anaerobic bacteria, occurs in the absence of oxygen. As a result of waste degradation, this process produces landfill gas. This gas, primarily carbon dioxide (CO_2), and methane (CH_4), can be captured to minimize greenhouse gas emissions and for energy production.
- **Hybrid** (Aerobic-Anaerobic) - The hybrid bioreactor landfill accelerates waste degradation by employing a 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 (operation as an anaerobic bioreactor) compared to the typical "dry tomb" landfill where no liquids are added.

To better understand the benefits of a bioreactor, it is important to have a general understanding of the biological degradation of solid wastes. The following is a brief summary of the degradation process that occurs naturally in landfills.

1.1.2 Biological Degradation of Solid Wastes

Municipal solid-waste stabilization in a sanitary landfill can be separated into two major biological stages:

- An aerobic degradation phase, which happens almost immediately after waste placement
- An anaerobic degradation phase, which develops once the oxygen originally present in the landfill is consumed

The large amount of organic matter in solid wastes allows biodegradation to proceed. Food and yard organic wastes, which are generally the first components of solid waste to undergo biodegradation, typically make up approximately 27% of MSW (municipal solid waste).

Aerobic Degradation

Aerobic degradation of organic matter occurs first in the degradation sequence. Bacteria begin to grow on the surface of the biodegradable fractions of the wastes and start metabolizing the waste by hydrolyzing complex organic structures to simple, soluble molecules. Cellulose, hemicellulose, and proteins are converted to soluble sugars and amino acids during this phase.

Leachate produced during the aerobic phase also is characterized by the dissolution of highly soluble salts initially present in the landfill. The leachate formed during this initial phase is most likely a result of moisture that was squeezed out of the wastes during compaction and landfill filling operations. Little solids loss occurs during aerobic degradation. This aerobic degradation phase is generally short because of the high biochemical oxygen demand (BOD) of the solid wastes and limited amount of oxygen present in a sanitary landfill.

Anaerobic Acid Production

Once the oxygen is exhausted, the microorganisms cannot completely metabolize the soluble sugars and amino acids and begin to break it down to organic acids which are readily soluble in water. As a result, soluble organic acids begin to accumulate in the landfill. The microorganisms involved in these processes obtain energy for growth from the chemical reactions that occur during metabolism and a portion of the organic waste is converted into cellular or exocellular material.

As the initial anaerobic biodegradation processes occur, the organic-acid accumulation yields a low pH leachate and considerable concentrations of inorganic ions (e.g., Cl, SO_4, Ca, Mg, Na). The increase in cation and anion concentrations probably results from the leaching of readily solubilized materials including those originally available in the solid waste and those made available by biodegradation of organic matter.

Methanogenic Degradation

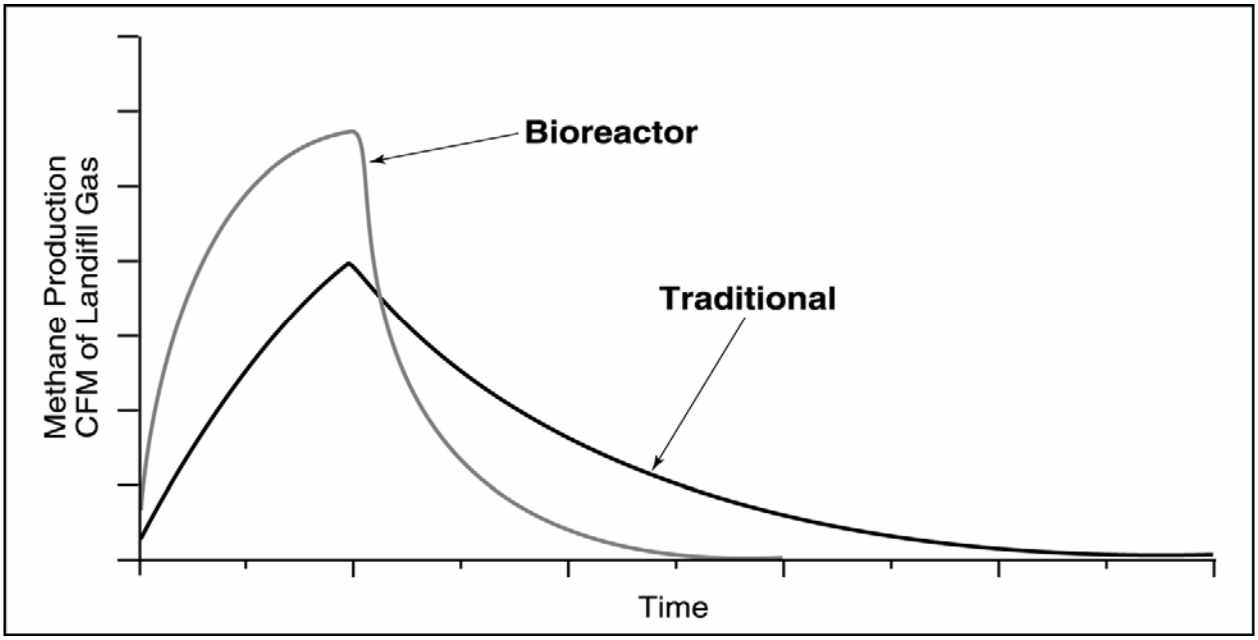
The second stage of anaerobic biodegradation is characterized by methane fermentation by methanogenic bacteria. The anaerobic conditions and the soluble organic acids create an environment where the methanogenic bacteria can grow. The methanogenic bacteria utilize the end products from the first stage of anaerobic degradation and convert them into methane and carbon dioxide. Methane fermentation generally begins within one year following solid waste placement (Walsh and Kinman, 1979). The methanogenic bacteria prefer a relatively neutral pH (6.6 to 7.4) and do not like acidic conditions. The acid formation in the first stage tends to lower the pH and if acid formation is excessive, the activity of the methanogenic bacteria can be inhibited.

1.2 Bioreactor Process Overview

The primary function of the bioreactor landfill is to accelerate the degradation of MSW. Research indicates that a bioreactor may generate LFG (landfill gas) earlier and at a higher rate than traditional dry landfills. In a bioreactor, LFG is also generated over a shorter period of time because LFG generation declines as the accelerated decomposition process depletes the source waste. The net result appears to be that the bioreactor produces more LFG during the period when the landfill is operating, than the traditional landfill. Most modern MSWLFs (Municipal Solid Waste Landfills) do not install gas collection systems until after site closure and landfill capping is complete. A typical bioreactor will have and operate gas systems during the active life of the landfill and collect and control gas over a shorter period of time.

Some studies indicate that the bioreactor increases the feasibility for cost-effective LFG recovery, which would reduce fugitive emissions. This offers an opportunity for beneficial use of bioreactor LFG in energy recovery projects. The US Department of Energy estimates at http://www.epa.gov/epaoswer/non-hw/muncpl/landfill/bioreactors.htm that "if controlled bioreactor technology were applied to 50 percent of the MSW currently being landfilled, 270 billion cubic feet of methane could be recovered each year. This LFG volume could be used to produce one percent of US electrical needs."

Figure 1-3 depicts a typical gas production curves from a dry tomb landfill and a bioreactor simulating the expected first order biological decomposition rate (K) expected under bioreactor operation vs. the Subtitle D landfill with no liquids added using USEPA's Landgem model.



CFM=Cubic Feet per Minute

Figure 1-3. Typical Landfill gas prediction curve for Bioreactor Landfill vs. Traditional Subtitle D Landfill ***(From Waste Management, Inc.)***

1.2.1 Liquid Amendments

Most landfills do not generate sufficient volumes of leachate to increase moisture content of MSW from an average ambient moisture content of 20 to 25 % by wet weight to optimal levels of 40 to 60% by wet weight. While this may be a significant operational goal, it may be very difficult to ensure that all of the waste material attains field capacity. Even if the waste material does not achieve field capacity, the addition of moisture will enhance waste degradation.

Liquids from outside the landfill boundaries will be required. Specifically, water or aqueous amendments (>50% water) are the most beneficial to increasing the population of bacteria that are naturally present in the landfill to optimize their performance in generating gas, degrading the organic fraction of MSW, and providing a treatment zone for leachate generated by the landfill. Non-hazardous organic amendments that are degradable also provide nutrients for the bacterial population. It is important, however, to use the appropriate amendments that enhance methane fermentation, since this is the principal stage of degradation of MSW where landfill gas provides over 55% methane that can be beneficially used as an alternate energy source. It is essential to understand the phases of waste decomposition to ensure that the landfill is in the right "zone" of optimal degradation as discussed in the following section.

USEPA has provided guidelines for acceptable liquid waste streams that could be added to a bioreactor landfill under the RD&D rule. USEPA's RD&D rule was established in recognition of the fact that most large landfills lack sufficient leachate to increase moisture content in MSW in a time efficient manner. However, the RD&D rule also allows other on-site liquids that also can be added including precipitation run-on, stormwater, surface water, and groundwater. The following guidelines are recommended for identifying potential off-site liquid amendments that may be available in the marketplace near the bioreactor landfill:

- Liquid amendments that are between pH of 4 to 9 and must be non-hazardous by characteristic and definition
- Liquids amendments that are 95-99% aqueous
- Liquid amendments currently accepted by bioreactor demonstration sites are
  - biosolids (2 to 9 % fresh or treated sewage sludge from POTWs (Publicly Owned Treatment Works (from raw sludge, digestors or lagoon clean-outs)
  - liquid rejects from food and beverage manufacturers
  - paint rejects or paint spray booth materials (acrylic water based paints)
  - tank clean-outs and oily waters(95% aqueous)
  - antifreeze waters, dye and ink test waters, dry well water
  - leachates from other sites
  - liquid sludge from non-hazardous waste treatment plants (commercial and industrial)
  - remedial liquids from companies that specialize in remediation and transport
- High concentration of soluble and degradable organic liquids

Liquids not acceptable include:

- Surfactant based fluids, oil or petroleum based fuels, pickling wastes, aluminum dross, and high sulfur content wastes
- Liquids that can be degraded quickly to simple sugars, such as tomato food rejects, should be used in combination with other aqueous amendments to avoid rapid fermentation to volatile acids
- Liquids with total phenols > 2000 ppm
- Liquids that are sulfide or cyanide reactive, ignitable, or corrosive
- Liquids that may be classified as hazardous waste or substances

These amendments or liquids are not acceptable because in sufficient quantities, they could potentially retard acceleration into the methanogenic phase of degradation of MSW (Phase IV) (See Figure 1-4 in the following section for a description of the phases of degradation and cause the landfill to remain in the acid phase (Phase III). However, small quantities of non-hazardous liquids not recommended above can be blended with acceptable liquids if the net result renders the combined liquid amendment with suitable characteristics.

The most likely liquid available to bioreactor landfills in substantial quantities would be POTW biosolids and effluents. Disposal of biosolids often presents a great challenge to (POTWs) as land treatment disposal options are becoming less viable. This is due to existing mature land application sites reaching their absorptive capacity for attenuating metals and other pollutants. There are a number of ways of managing and disposing of biosolids; the most popular and cost-effective method is co-disposal at MSW landfills. Existing solid waste regulations require that biosolids be solidified sufficiently to pass the paint filter test. This results in a solids content of 22-25% by wet weight. By using of biosolids prior to solidification, POTWs can save money and energy by avoiding further processing and the bioreactor landfill can benefit from the high water content, bacteria, enzymes and nutrients.

The earliest work in lab scale leachate recirculation demonstration by Dr. Fred Pohland in 1975 showed that addition of biosolids enhanced the beneficial results of leachate recirculation alone in increasing settlement, gas production, and leachate treatment. USEPA sponsored studies at the Office of Research and Development (ORD) in the early ‘80s showing the increase in gas production as a result of co-disposal of biosolids and MSW. Other studies by Leuschner (1989) and New York State Energy Research Development Authority (1987) all showed positive affects for early gas production. A recent study by Reinhart et al, 2005 showed that co-disposal of biosolids has several benefits comparable to a bioreactor landfill at full scale landfills, especially in increasing rates of gas production. USEPA also views this as favorably controlling green-house gases while the facility is active as opposed to long-after closure. These advantages make biosolids co-disposal in landfills very effective in increasing degradation and treatment of both MSW and sludge.

There are a large number of industries that may be near bioreactor landfills that have to pre-treat their liquids left over from production of goods and materials before discharge directly into the City sewer system. These industries may benefit in savings for pre-treatment and residuals management by taking suitable liquids directly to the Bioreactor Landfill. There also are other industries that have direct discharges (NPDES permits) that could be diverted into the landfill that could save on treatment, monitoring and reporting costs. Diversion of these liquid amendments into the Bioreactor Landfill also benefits the environment. It reduces the amount of pollutants that enter the air from treatment facilities and pollutant loads that enter surface water. There will be controlled emissions at the landfill with the collection and control of landfill gas and there will be no discharges into surface water directly from the landfill or leachate.

1.2.2 Phases of Waste Decomposition

In order to understand the principles of the landfill operated as a bioreactor, it is important to understand the degradation characteristics or “life cycle” of an MSWLF. Municipal solid waste can be rapidly degraded and constituent concentrations reduced (due to degradation of organics and the sequestration of inorganics (e.g. bind them so they it will not flow into the leachate or release from the landfill)) by enhancing and controlling the moisture within the landfill under aerobic and/or anaerobic conditions. Through recirculation of the leachate and degradation, leachate quality from a bioreactor can rapidly improve, which leads to reduced leachate disposal costs. According to Pohland et al (1986), there are five distinct phases of waste decomposition as shown in Figure 1-4. Each phase, characterized by the quality and quantity of leachate and landfill gas produced, marks a change in the microbial processes within the landfill.

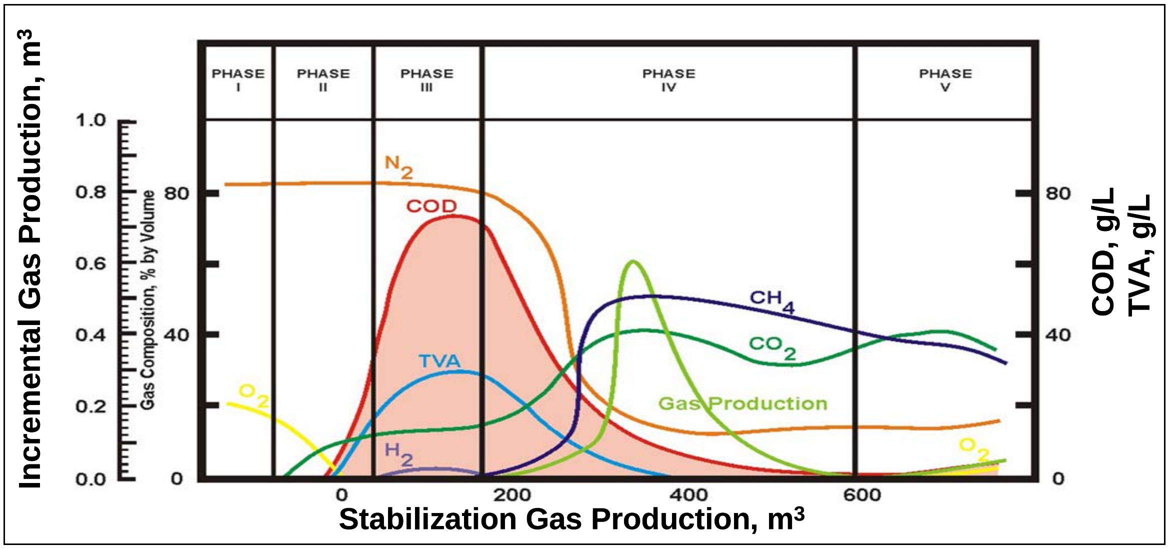


Figure 1-4. Waste decomposition phases taken from draft
(Modified from Pohland and Harper, 1986)

Phase I (lag phase) is an acclimation period in which moisture begins to accumulate and the oxygen entrained in freshly deposited solid waste begins to be consumed by aerobic bacteria.

Phase II (transition phase) The moisture content of the waste has increased and the landfill undergoes a transition from an aerobic to an anaerobic environment as oxygen is depleted. Detectable levels of total volatile acids (TVA) and an increase in the chemical oxygen demand (COD) of the leachate signal the increased activity of anaerobic bacteria.

Phase III (acid phase) The rapid conversion of waste to TVAs by acidogenic bacteria results in a decrease in leachate pH in Phase III. This phase is the initial hydrolysis where liquid leaches out the easily degradable organics. The rapid degradation lowers pH to make it more acidic, and mobilizes metal species that migrate from the waste into the leachate. Volatile Organic Compounds (VOCs or solvents) are also mobilized. This phase is characterized by peak COD and BOD levels in leachate.

Phase IV encompasses the period in which the acid compounds produced earlier are converted to methane and carbon dioxide gas by methanogenic bacteria. This phase marks a return from acidic conditions to neutral pH conditions and a corresponding reduction in the metals and VOC concentrations in leachate. This phase marks the peak in landfill gas production. The landfill gas production and COD/BOD cycle follow similar first order biodecay constants.

Phase V marks the final stage or maturation to relative dormancy as biodegradable matter and nutrients become limiting. This phase is characterized by a marked drop in landfill gas production, stable concentrations of leachate constituents, and the continued relatively slow degradation of recalcitrant organic matter.

1.3 Advantages and Disadvantages of Bioreactor Landfills

As with many new technologies there can be associated advantages and disadvantages of bioreactor landfills. Advantages provided by bioreactors landfills are discussed below as primary and secondary. Some of the disadvantages associated with bioreactor landfills can be mitigated by the design to accommodate the potential issue. Design issues are discussed later in the design section of this guidance.

1.3.1 Primary Advantages for Bioreactor Design

Bioreactor landfills offer much potential as a viable waste disposal technology. These include;

- Primary advantages
  - Efficient utilization of permitted landfill capacity
  - Stabilization of waste in a shorter time
  - Reduced leachate handling cost
  - Reduced post closure care
- Secondary Advantages
  - Optimization of waste emplaced in a landfill
  - Potential for landfill gas to be a revenue stream
  - Reduced air emissions containing VOC and HAPs
  - Obtaining an advantage from alternative cover designs
  - Reduced toxicity of leachate and waste material
  - Consistentcy with sustainable landfill design

With the public issues related to "Not In My Back Yard (NIMBY) opinion/positions regarding the siting of new landfill facilities and the promulgation of tougher, more stringent, solid waste management regulations, permitting of new disposal facilities has become increasingly difficult. The solid waste management industry has been forced to explore opportunities to maximize waste disposal capabilities, and to efficiently utilize permitted capacities to extend the life of existing facilities. The concept of accelerated decomposition of waste to gain additional airspace within the landfill footprint has lead to a relatively new way to look at waste disposal. Acceleration of waste decomposition can lead to enhanced landfill stability and decreased risks of landfill releases coupled with regenerated and useable air space. These practices integrate risk and liability management with the reduced siting, permitting, design, and construction of new landfills.

When evaluating the bioreactor landfill concept, three primary advantages can be identified. First, decomposition and biological stabilization of the waste in a bioreactor landfill can occur in a much shorter time frame than what occurs in a traditional dry tomb landfill. As a result, decomposition and biological stabilization of the waste pile can be reduced to years as compared to decades for traditional dry landfills. The result of this rapid decomposition and stabilization can be an estimated 20 to 40 percent gain in landfill airspace due to reducing the volume and increasing the density of the in-place waste. If the resulting volume reduction of the waste can be reclaimed and additional waste placed in the facility, then revenues generated by this additional waste capacity can offset some or all of the costs of operating a bioreactor type landfill. Furthermore, there are real cost savings in continued operations of an already established waste disposal site. Continued use of infrastructure already in place is almost certainly more beneficial than construction of a new facility at a different location.

The second major advantage to the bioreactor concept occurs in the form of reduced leachate handling costs. Liquids addition is one of the key components necessary to make a bioreactor landfill function properly. Landfill leachate is often used to partially satisfy this liquid requirement. The leachate generated by the existing landfill is a readily available source for a portion of the necessary liquid. In many cases, the amount of money saved by not having to treat or dispose of the leachate or otherwise handle the leachate can produce enough cost savings to justify pursuing a bioreactor landfill.

In order to get the waste pile to the desired liquid content, other types of liquid wastes could potentially be accepted at the landfill. Although regulatory barriers may currently exist with regard to this concept, as bioreactor landfills gain acceptance, liquids restrictions currently in place may be re-evaluated. Therefore, the need to add liquid to the landfill to make a bioreactor work properly can result in reduced leachate handling costs and increased revenues generated by previously unacceptable waste streams.

The third major advantage to the bioreactor concept concerns the possibility of reducing the amount of post-closure care that is necessary for the facility. This is further discussed in the ITRC's Technical Regulatory Guidance for Ending Post Closure Care and Landfills (ITRC ALT-4 in progress) and EREF's (Environmental Research and Education Foundation 2006) A Performance Base System for Post Closure Care at MSW Landfills (in progress): A procedure for providing long-term stewardship under RCRA that is necessary for the facility. Currently, regulatory agencies show resistance to deviating from the standard post-closure care periods (i.e. 30 years), however, should the bioreactor concept prove to be successful, these regulatory barriers may ease. As the processes involved in the bioreactor process degrade waste, research indicates that the waste (solid waste and leachate) may become less of a threat to human health and the environment. Leachate quality in a bioreactor can improve with time. Also, the waste pile becomes more stable as the density rises. Given this, a good case can be made for reducing the length and types of post-closure care for bioreactor landfills. If the overall length of the post-closure care period cannot be reduced, it is still possible that individual aspects of post-closure care can be evaluated and reduced or even eliminated. As a result, significant savings might be realized with a reduced length or complexity of post-closure care, in addition to having a closed landfill that presents a reduced threat for contamination of the environment.

1.3.2 Secondary Advantages

As previously stated, one of the primary benefits of the bioreactor concept is the optimization and maximization of the amount of waste that can be placed in a given landfill design. The increased density and reduced volume of waste resulting from enhanced waste decomposition could mean that existing landfills can remain in operation longer. A secondary benefit from the efficient use of existing landfill capacity is the need for fewer landfills placed in green spaces. Resources normally tied up by both the regulatory agency and the permittee to site and permit new landfills can be put to use monitoring and operating those facilities already in existence.

Other secondary advantages can exist when the bioreactor concept is applied to landfills. For example, landfill gas (LFG) is generated earlier in the landfill operation for bioreactors than for traditional dry landfills. As a result, operational advantages associated with the generation of LFG can be realized sooner. These include direct income associated with the use or sale of the gas and the indirect advantage of increased LFG generation early in landfill operation. Diminishing gas generation late in landfill closure and post-closure period provides another basis for reducing the post-closure care period. Certainly, early incorporation of LFG collection and management system are important parts of bioreactor landfill design and construction. This aspect is given appropriate emphasis in later sections of this guidance manual; however, certain disadvantages also can be the result of increased early generation of LFG, such as potential release to the atmosphere and gas-related impacts to groundwater.

Land fill gas emitted by a bioreactor landfill will consist primarily of methane and carbon dioxide plus lesser amounts of non-methane organic compounds (NMOCs). According to the USEPA 2005, LFG generated by bioreactors may contain lower concentrations of VOCs and HAPs, thus reducing air emissions issues associated with the release of NMOCs to the atmosphere.

Alternative final landfill covers (AFC)(See ITRC ALT-2, 2003) may be particularly beneficial for bioreactors. Bioreactors need moisture unlike conventional “dry tomb” landfills. Alternative final covers can be designed and constructed, in almost all settings, to control the amount of infiltrating moisture from precipitation at bioreactors landfills. These AFC designs can offer cost savings when compared to conventional landfill covers used for conventional landfills or bioreactor.

Another secondary advantage of bioreactor landfills is the potential for lower toxicity and immobility of chemicals in the waste due to enhanced aerobic and anaerobic conditions within the landfill. The degradation processes active in bioreactor landfills typically go through several phases during the life of the landfill. Organic compounds present within the landfill are broken down by microbial action, and the threat of a release of toxic organic compounds is reduced. Metals may become more mobile or less mobile as the alkalinity and pH changes as a result of landfill phase changes. However, over time the overall lower toxicity of landfill leachate should reduce the threat to human health or the environment associated with contamination of groundwater should a release occur.

A sustainable landfill concept blends the act of allowing or encouraging the in-place waste to degrade (organics) and chemically bind (inorganics) and then mining the degraded material for recovery and reuse.

If the bioreactor landfill were to be used in concert with the concept of a sustainable landfill, bioreactors would have the secondary advantage of allowing a cost-effective total reclamation of the landfill airspace. When stabilized, the degraded waste could be excavated using the process of landfill reclamation. Stabilized waste would consist of a compost-like material, soil, and large non-degradable items. The compost and soil could be recovered by screening, and the remaining non-degradable material, can be re-landfilled with little environmental risk. Some non-degradable materials such as metals and glass may even be recovered from the waste stream for recycling. Then the former landfill footprint could be available for reuse as a landfill, perhaps restarting the bioreactor process.

1.3.3 Potential Disadvantages Associated with Bioreactor Systems

Bioreactor landfills definitely hold much potential as a viable waste disposal technology. However, there are uncertainties associated with uses of the technology such as:

- Confusion over existing regulations to permit bioreactors
- Higher capital costs
- Operator skills
- Temperature control in aerobic bioreactors
- Geotechnical stability
- Liner chemical compatibility
- Odor control
- Availability of liquids

While some regulatory agencies believe they can permit bioreactors under their existing regulations, many regulatory agencies believe that the prohibition on liquids addition to landfills, other than leachate, precludes them from permitting fully functional bioreactors. Therefore, for many regulatory agencies there is not currently available means to permit the long term use of bioreactors other than through the RD&D rule provisions. Of the twelve states responding to a questionnaire from the team, seven indicated they use the same process to permit a bioreactor as they do a conventional landfill.

The concept of liquids addition to the waste pile to accelerate the decomposition of waste appears contrary to the design requirements of current regulations. Current landfill regulations require that the waste pile be kept as dry as possible during the life of the landfill, including the post-closure period. As a result, particularly early in the progression of permitting bioreactor landfills, resistance, and a lack of familiarity from the regulatory body and the public can be anticipated.

In its questionnaire to the states, the team also asked if the state had statutes, regulations, policies, or guidance pertaining to liquid addition to a landfill cell or waste material with the new RD&D rule. Two-thirds of the states responding indicated they had no such rules. Facilities pursuing a bioreactor landfill should anticipate delays in the permitting process as issues brought forth by the regulatory body and the public will need to be adequately addressed possibly through additional public outreach and education. The additional community outreach and education may be above and beyond the specified regulatory requirements, but of great benefit to the facility and the project. The likelihood of appeal of the permitting decision may also be higher for new bioreactor landfills.

There is no question that bioreactors may have long-term cost benefits due to the potential for reduced long-term risks and recovery of reusable airspace, however, there are additional short-term costs associated with bioreactor landfills. For example these systems require additional engineering, construction, and operational costs due to the complexity of the process. Bioreactor landfills of all types are more complex in construction and operation, particularly if waste decomposition is to be maximized. Bioreactor landfills contain engineered systems that have higher initial capital costs and require additional monitoring and control during their operating life. The bioreactor landfill will also require a much higher level of oversight and operator skill to maximize operations and to modify the system as needed. Consequently, bioreactor landfills require a more complex set of operations and maintenance (O&M) procedures than conventional landfills. Additionally, liquid delivery systems must be designed and installed at various stages of landfill operation, which increases the chance of damage to the liquid delivery system and adds to the complexity of conducting day-to-day operations. Therefore, some waste disposal facilities, with limited resources, may find it difficult to retain the appropriate level of design, construction, and operator skills to successfully implement a bioreactor landfill project. All of these costs must be factored into the decision making process when evaluating the cost effectiveness of a bioreactor process.

In landfill bioreactor systems designed to aerobically decompose the waste, the addition of oxygen can increase the chance of internal fires at the landfill. Since aerobic processes within the waste pile operate at higher temperatures than anaerobic processes, temperature control within the waste pile becomes a critical factor. As a result, temperatures within the landfill must be closely monitored at all times to ensure that a fire does not start within the waste. These types of landfill fires are typically the most difficult to control, and could damage fluid delivery and containment systems needed to add liquids and oxygen to the waste pile. Similarly because these processes generate higher internal temperatures within the waste pile, it may be necessary to upgrade fluid delivery systems to more heat resistant materials. Retrofitting and repairing damaged systems after the landfill has been constructed is costly, difficult, and in some cases impracticable.

The goal of most bioreactor designs is to raise the liquid content of the waste pile to a level close to field capacity. As the waste pile becomes increasingly wet, geotechnical stability of the waste pile can become an issue. As the liquid content of the waste rises, slope stability can decrease along the perimeter of the landfill. By minimizing the amount of liquids added to the perimeter of the landfill, this condition can be controlled, but must be closely monitored nonetheless. In addition, as the waste pile degrades during operation, settlement will not be uniform over the surface of the landfill. This differential settlement can cause internal stresses on the landfill systems, in addition to causing possible operational problems such as liquid distribution. The issue of surface seeps and breakouts may become a compliance issue, which will need to be addressed during the operational life of the facility as well as the post-closure period.

There is some concern that the bioreactor process may have an adverse impact on synthetic liner systems. Because aerobic processes in general operate at elevated temperatures, this increase in temperature may cause a breakdown of the polymers in the main liner system. Certainly there is the need for research into the long-term effects of the process on the components used to construct today’s landfills. A key environmental condition for a geomembrane (as well as other geosynthetics) is its in-situ temperature.

Dr. George Koerner (2005) reports that using thermocouples attached to geomembrane liners and covers at two landfills containing municipal solid waste, long-term temperature data has been obtained at dry (conventional) and wet (bioreactor) landfills. Data indicates that liner temperatures beneath the solid waste at dry landfills are lower than at wet landfills. Cover temperatures, however, are controlled by ambient temperatures at the site and show a pronounced annual cyclic behavior. The data is particularly intriguing since temperatures were constant at 20°C for the first four years and then abruptly increased to a 30°C average. The cover temperatures swing seasonally; higher in summer and lower in winter. An additional effort in this regard is the monitoring of the geomembrane liner and cover temperatures in a bioreactor landfill in Pennsylvania. The geomembrane beneath the waste was at an average temperature of 25°C (5°C higher than the dry landfill) at the start. It has gradually risen over the past 2.5-years to an average temperature of 40°C (approximately 10°C higher than the dry landfill).

Although one of the benefits of the bioreactor process can be enhanced LFG generation, this aspect of the process also can be a potential disadvantage. With many landfills being located in close proximity to residences, the problem of nuisance odor control (associated with NMOCs in LFG) already is an issue. The necessity for consideration of LFG collection and management during bioreactor design and early implementation of those controls and management methods, probably from the beginning of landfill operation, could be disadvantages (financial and operational) for bioreactor landfills as compared to traditional dry landfills. Also, failure to keep the gas collection system operating acceptably could increase public discontent toward a particular landfill, and could result in the permitting authority requiring additional measures to reduce nuisance odors and potential methane migration issues.

Bioreactor landfills require significant quantities of liquids be added to the waste pile. This increase in liquids in the landfill can place stress on the leachate collection system. The leachate collection system must be designed, constructed, and operated to handle these additional liquids. Additional safeguards may be necessary during the design of the leachate system to address biofouling, mechanical fouling of the piping in the collection system and the need for additional pipe cleanouts. Furthermore, if the system does experience a failure, the risk of contamination to groundwater may be increased, depending upon the constituents in the leachate.

1.4 Project Overview of Full Scale and Demonstration Bioreactor Projects

EPA and its state and industry partners are studying and conducting research and demonstrations on bioreactor landfills and other landfills, such as those that recirculate leachate. The following is a list of the bioreactor research studies, demonstrations, and guidance projects currently underway within EPA.

1.4.1 Project XL Bioreactor Landfill Pilots

Project XL (eXcellence and Leadership) is an EPA initiative begun in 1995. The program provides limited regulatory flexibility for regulated entities to conduct pilot projects that demonstrate the ability to achieve superior environmental performance. The information and lessons learned from Project XL are being used to assist EPA in redesigning its current regulatory and policy-setting approaches. As of September 2001, four landfill pilot projects have been approved to operate as bioreactors. These landfill pilot projects include:
- Buncombe County Landfill, North Carolina – http://www.epa.gov/projectxl/buncombe
- Maplewood Landfill, Virginia – http://www.epa.gov/projectxl/virginialandfills
- King George County Landfills, Virginia – http://www.king-george.va.us/reports2.cfm?tid=2&storyid=21
- Yolo County Bioreactor Landfill, California – http://www.epa.gov/projectxl/yolo/index.htm

EPA provided these facilities with the regulatory flexibility to allow them to recirculate leachate and other liquids over a municipal solid waste landfill unit constructed with an alternative liner system. In turn, the designers of these bioreactor XL projects hope that, when implemented, the leachate re-circulation/gas recovery landfill approach will provide superior environmental performance by

- enhancing groundwater protection;
- reducing landfill gas emissions by early installation of, and operation of, gas collection and control systems;
- increasing waste capacity and lengthening life of existing landfill cells, thereby reducing the need for new landfill sites, and;
- improving leachate quality and ultimately cleaner wastewater discharges.

The pilot demonstrations are expected to be completed according to the agreed-upon duration for each individual project, between 2006 and 2026. The evaluations will be ongoing, and will be completed shortly after each pilot is completed.

1.4.2 Cooperative Research with Waste Management using a CRADA

EPA's National Risk Management Research Laboratory has partnered with Waste Management, Inc. (WM) to conduct research on several large-scale bioreactor landfills looking at several variables. This work is being conducted through a Cooperative Research and Development Agreement (CRADA). The purpose of this five-year, joint research effort is to collect sufficient information in order to ascertain the best operating practices to promote the safe operation of bioreactor landfills.

Various design and operating features are being studied, including (1) semi-aerobic, and (2) facultative waste decomposition processes. The CRADA is in effect from 2001-2006. Results of this project will be used to assist in the development of bioreactor guidance documents and standard operating procedures. Progress reports are available through conference proceedings or by contacting WM directly.

1.5 Summary

Operation and design of a bioreactor landfill is not a new technology. Many bench scale and pilot scale field demonstrations have been successfully completed. US Environmental Protection Agency (EPA) sponsored research with this technology since the 1970s. Promulgation of RCRA and CERCLA forced many US bioreactor facilities to cease operation. However, the adoption of Subtitle D and research by USEPA has stimulated new demonstrations of the positive impacts bioreactor landfills provide for managing municipal solid waste. Landfills need a Subtitle D liner or equivalent and adequate leachate collection. Early and adequate gas collection system should manage the increased rate of gas collection resulting from liquid introduction into the landfill. Permeable material such as select inert C&D waste (excluding reactive material e.g. pulverized sheetrock), foams, tarps, etc should be used as daily cover that will not block or hinder movement of recirculated leachate and moisture throughout the waste mass. The foregoing issues will be discussed in greater detail in Sections 3 and 5 of this document. Successful bioreactors could potentially increase the life of the landfills from 20 to 40% and avoid costly siting and permitting of a new landfills.

2.0 REGULATORY BACKGROUND

In recognition of the need for national standards for the design and operation of landfills, Congress enacted and the USEPA wrote the regulations to implement Subtitle D of RCRA. These rules became effective in 1993 and prescribed landfill design, operation, and post-closure practices such as composite liners and covers (low permeability soil plus geosynthetic membrane), the prohibition of liquid wastes, installation of leachate collection systems, and monitoring requirements that together form the basis of the modern sanitary landfill.

Subtitle D requirements successfully reduced the potential for leachate to escape, and create negative impacts to human health and the environment from the modern landfill. Engineered liners, in combination with leachate collection systems, prevent the migration of leachate from the bottom of the landfill into the earth and groundwater. The requirement for low permeability caps reduce the potential for leachate generation further by minimizing the major source of moisture (infiltration of precipitation) from entering the waste. The resulting sanitary landfill today is a highly engineered and secure waste isolation repository. However, it is also a dry tomb that retards the microbial activity necessary for biological and chemical degradation and resulting waste stabilization.

The application of bioreactor technology at an unlined landfill is difficult from a regulatory perspective because liquid addition is prohibited in an unlined landfill. There may be unusual exceptions where naturally occurring shales or clay formations might be construed as an adequate liner, however it may be;

- regulatorily impractical and expensive,
- geologically rare and expensive, and
- the engineering is expensive

EPA was aware of the dilemma posed by designing moisture out of landfills while at the same time trying to achieve waste stabilization. The preamble to the Subtitle D regulations includes:

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

Also, liquid addition to the landfill could be permitted, but only by way of liquids recirculation as allowed for in 40 CFR 258.28(b)(2).

USEPA is aware that most large landfills do not generate sufficient volumes of leachate to optimize degradation. Bioreactor demonstrations and data from liquids recirculation landfills have convinced USEPA to promulgate the Research Demonstration and Development regulation FR 69 No. 55, pp. 13242-13256 (attached in Appendix D). This regulation allows authorized States that adopt it to issue research permits for 3 years (renewable 4 times) to landfills that want to demonstrate new technology. For bioreactors, the regulation allows non-hazardous liquid wastes to be added to the waste to increase moisture in the landfill. The rule also allows alternate caps and delay of final capping to increase biodegradation and settlement of the landfill. As of 2005, a team questionnaire found that only one of the twelve states responding has adopted the new RD&D rule but half of the states indicated they plan to adopt it. This would appear to indicate state interest in bioreactor technology.

2.1 RCRA Regulations and Guidance

The key federal legislation governing the closure of landfills was written in the early 1980s, and the beginning of the remediation programs for the correction of past disposal practices followed shortly thereafter. RCRA is the controlling federal law for both municipal solid waste and hazardous waste landfills.

2.2 Flexibility in State Solid Waste Regulations

Most of the emphasis in the federal solid waste regulations is placed on keeping liquids out of landfills. While majority of the states contain regulations prohibiting “free” liquids from being placed into landfills, these state regulations do contain provisions for allowing the recirculation of leachate back into the landfill system. A few states, however, have regulations that allow for the permitting of a bioreactor even before the RD&D rule.

3.0 DESIGN CONSIDERATIONS FOR BIOREACTOR LANDFILLS

This chapter provides fundamental concepts of bioreactor design. The design of a state-of-the-art landfill, augmented by the principals of bioreactors technology, involves a myriad of scientific and engineering disciplines, including but not limited to, geology, hydrology, civil, geotechnical and materials (i.e. geosynthetics) engineering. In addition, biological and chemical waste decomposition, gas and leachate quality and quantity resulting from landfill operations must be evaluated and factored into the design. It is beyond the scope of this guidance document to provide complete information on each and every design concept of landfills. The guidance provided in this chapter is not meant to be all-inclusive since a bioreactor design requires a multi-disciplinary approach. Many excellent reference materials are available for various parameters of design, and research continues. The current literature and research should always be reviewed in conjunction with this guidance to understand the current development in this rapidly growing technology.

According to EPA (2003), there are approximately 2500 permitted Municipal Solid Waste Landfills (MSWLFs) currently in operation in the United States. Approximately 10% of these facilities will involve retrofitting bioreactors and commence liquids recirculation on existing landfill infrastructures. Current trends indicate that between 10 and 15 new landfills are being constructed each year, with between 2 and 4 facilities are being constructed as bioreactors.

Bioreactor features may be incorporated into any new landfill design so that all bioreactor operational elements are addressed during the initial permitting process for a facility, or a bioreactor may be retrofitted onto an existing facility. There are advantages to designing a landfill as a bioreactor from the initial planning stages of the project. These advantages may include accommodating the specific needs of the bioreactor into the design, construction, operation, closure, and post-closure care elements of the landfill. For example the landfill may be filled in a method, such as back-sloping the lifts of MSW to reduce the potential for seeps, the use of alternative daily cover to improve fluid distribution, the installation and operation of liquids addition systems at various levels coincident with the filling operations, and the use of compaction methodologies to enhance fluid migration. While all of these, and other design and operating criteria, may be easier to manage if they are designed and built into the landfill from the outset. These advantages may result in cost and resource savings while optimizing the results of the bioreactor operation. However, given the number of existing landfills that may be suitable as bioreactors, retrofits bioreactors may be implemented in greater numbers and very successfully. Retrofit bioreactors landfills may require more iterative learning to optimize the use of resources and bioreactor productivity than a design-initiated bioreactor. The iterative learning practice of landfill operation and optimization is depicted in Figure 1-2.

As discussed previously, three general types of bioreactor landfills can be considered during the early design process. First, an *anaerobic bioreactor* landfill promotes accelerated waste degradation and methane gas production with waste stabilization. Second, an *aerobic bioreactor* landfill promotes accelerated waste degradation and non-methane gas production with waste stabilization. Third, a *hybrid bioreactor* landfill, which involves both processes, promotes accelerated waste degradation and results in final methane gas production with waste degradation. Any one of these types may be constructed as a new facility or as a retrofit to an existing landfill facility.

A landfill bioreactor will have additional capital and operating costs compared with conventional landfills. These costs can be offset by benefits including gas production, recovered airspace, and enhanced liability management through decreased threats to human health and the environment, and the possibility of reducing post-closure care. If the goal is to increase methane production for energy recovery, an anaerobic bioreactor is desired. The capital costs of constructing an anaerobic bioreactor may be partly offset by the increased gas generation rates and savings from leachate disposal costs. A cost-benefit analysis should be undertaken to evaluate these costs.

Also, no two bioreactors will be designed or operated exactly the same. These variations lead to different design considerations that are unique to the bioreactor setting, available infrastructure, applicable regulatory requirements, relevant stakeholder concerns, and materials. Operating criteria that are a benefit at one bioreactor, can present design and operating challenges in a different setting.

Below are potential operating considerations that should be evaluated during design, construction, and operation of bioreactors. Emphasis is placed on the term “potential”, because issues that may be an important at one facility may not be nearly as relevant at another. All of the items listed below can be addressed with thorough engineering and design:

- Management needs for increased volumes of landfill gas
- Increased Operations and Maintenance requirements
- Increased leachate management requirements
- Additional need for moisture for operational purposes

- Potential for increased odors
- Potential for increase explosion risk
- Potential physical instability of waste mass due to increased moisture and density
- Instability of liner systems due to increased weight from the increased density of the waste material. This should include consideration of other geotechnical characteristics and the overall stability of the landfill
- Surface seeps
- Landfill fires
- Climatic factors

Bioreactor landfills are engineered systems that may have higher initial capital costs and may require additional monitoring and control during their operating life, but are expected to involve less monitoring over the duration of the post-closure period than conventional landfills.

3.1 Site Selection Process

3.1.1 Site Considerations

Many factors must be considered when evaluating a site for potential development into a conventional sanitary landfill or bioreactor landfill. Some of these factors include public opinion, health, and safety, local geology, hauling distance, sufficient rainfall drainage, zoning, and land use requirements and economics. With these factors in mind, a site is selected based on its ability to

- Conform with local Solid Waste Management Plan;
- Conform with land use planning;
- Address community stakeholder concerns;
- Be accessible to haulage vehicles in all weather conditions;
- Provide adequate safeguards against potential surface and groundwater contamination;
- Provide adequate setback and buffer areas;
- Obtain large amounts of suitable soil for use as cover (daily, intermediate and final) material;
- Provide protection so that environmentally sensitive areas are not impacted during the landfill's operations;
- Be economically viable for the community it serves based on long-term solid waste generation projections; and
- Provide a potential beneficial end-use (i.e. recreational purposes such as a park or golf course) following landfill closure.

During the site selection process, other criteria also must be considered. For example, there are restrictions for siting a landfill on or near a floodplain, wetlands, unstable soils, fault areas, seismic impact zones, airports, and other constraints. If any one or more of these factors are present at the selected site, additional performance standards may be imposed on the design of any landfill type.

3.1.2 General Landfill Design Considerations

Once a site is selected, the landfill must be designed to satisfy all of the criteria established during site selection process. An important factor in a landfill design is establishing the size of the facility. Working on behalf of the developer (often a public entity such as a County government or Authority), the engineer estimates the quantity of waste the new landfill will receive using population data and current solid waste disposal rates. The analysis should factor in a projection of future population growth, commercial and industrial development, and recycling rates. Once these factors are analyzed, an overall volume for the landfill can be determined. The footprint and elevations of the waste disposal area are then determined. The design of the waste disposal area must also consider the site topography, site soils, groundwater flow, and access to cover material. The design also must consider the specific types and volumes of waste materials that will be disposed of in the landfill (i.e. municipal, bulky, vegetative, dry industrial and other wastes). The composition of waste types will largely determine the design of the liner system. To provide more stringent protection for groundwater (at a minimum a Subtitle D liner system or approved alternative), landfills may be designed with more than one liner system (often referred to as a composite liner system, which has one liner on top of another with a primary leachate collection system, or double liner system, which is constructed with a secondary leachate collection system).

Once the general layout and volumetric dimensions of the site are specified, the design shifts to specific details. These details include:

- Liner systems (using an appropriate combination of low permeability material such as natural clay or man-made geomembranes)
- Leachate collection and removal systems
- Gas collection and control systems
- Surface water controls
- Access roads
- Structures, including administration building and scalehouse
- Utilities
- Fencing
- Wash racks (to remove dirt from truck tires)
- Groundwater and landfill gas monitoring
- Landscaping

Once the engineer has designed each of the above systems, a permit application typically is prepared and submitted to the regulatory agency for approval. The permit application usually consists of several documents, including, but not limited to an environmental and health impact statement, engineering design drawings and specifications, operations plan and other agency specific requirements. Copies of the application are submitted to the regulatory agency and other government agencies, including the host community, for review and comment. Through the technical review process, the proposed design will be determined to satisfy (or not satisfy) pertinent solid waste regulations. Technical deficiencies or aspects of the proposed design that do not satisfy the regulations or current industry standards are brought to the applicant's attention for correction.

Bioreactor features may be incorporated into any new landfill design so that all design issues relating to bioreactor operations are addressed during the initial permitting process for a facility, or a bioreactor may be retrofitted onto an existing facility. In either case, the majority of design goals will be the same.

3.2 Research Affecting Design Parameters

Recent literature, conference proceedings, SWANA Bioreactor Committee, and USEPA sponsored workshops have shown positive results of liquids recirculation and appurtenant bioreactor technologies on landfills. Research on bioreactor technology provides a better understanding of interrelationships between liquids storage, field capacity, and densification of waste materials during the accelerated decomposition process. Based on these results, the optimum waste moisture for a bioreactor should be 10 to 20% above the levels of the incoming MSW. The moisture does not have to be introduced all at once or during each day of operation of the landfill, but can be added incrementally with liquids recirculation or make-up water over time. Some sites have recirculated leachate in the same areas for seven years and will not achieve field capacity for several more. Field capacity is a function of the types, age, density, and porosity of the deposited wastes. Also, field capacity will decrease with time, as the waste settles and increases in density. By recording the quantities of leachate applied to specific areas of the landfill where waste volume and tonnages are known, it can be determined when field capacity or (>forty percent waste moisture) has been achieved. (See Appendix F for a detailed set of calculations for field capacity by Qian, 2002)

Density of MSW has been observed to increase up to 100 percent of initial densities with a maximum expected density of ~2300 lbs/cy (density is estimated using the volume lost due to degradation as opposed to direct measurements). For example a bioreactor landfill in Minnesota had a starting density of 800 lbs/cy and after 4.5 years of recirculation had a final density of 1650 lbs/cy, over a 100% increase. Another bioreactor in Ontario, Canada started with an average density of 1000 lbs/cy and after 7 years of recirculation reported a final density of 1950 lbs/cy. A bioreactor cell in New Jersey had a starting density of 1150 lbs/cy and after 1.5 years of recirculation, ended up at 1890 lbs/cy. The operator injected over 12 million gallons into a 10 acre cell during that time frame. (Baker & Williams, 2001) the Outer Loop bioreactor demonstration project (at http://www.epa.gov/ord/NRMRL/pubs/600r03097/600r03097.htm) started at a density of 1450lbs/cy due to the additional liquid waste that were co-disposed and in about 1.2 years measured a density of 2000 lbs/cy. Typically a higher starting density of the MSW results in a higher density at the end. The rate of density increase is largely due to the amount of fluids available for recirculation (USEPA, 2003).

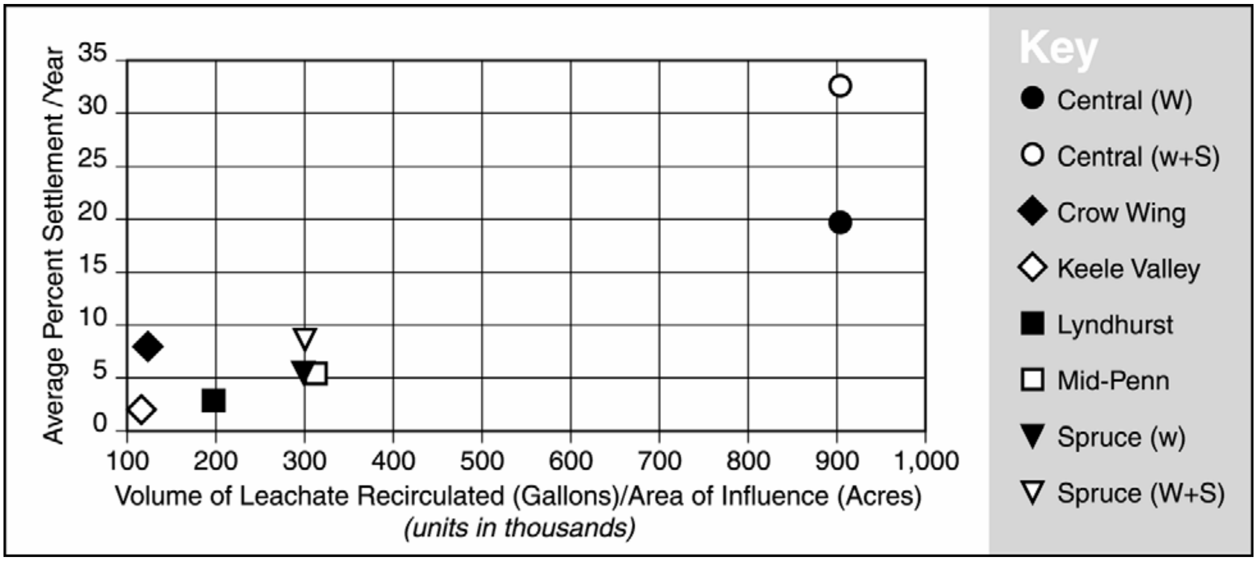


Figure 3-1. Average percent settlement /year vs. volume of leachate
(Baker & Williams, 2001)

Because increase in density is the inverse of settlement, Figure 3-1 shows the relationship of settlement responding to the amount of liquid added per area of influence in the landfill. This shows that the rate of settlement (and density) and the amount of leachate recirculated, or liquid added, per unit area is roughly correlated.

3.2.1 Recirculated (gallons) per Area of Influence (acres)

The predicted settlement from early bench scale tests that simulate a full bioreactor operation are shown below (Pohland, 1975). These graphs that are from Dr. Fred Pohland's work, show settlement occurring from the addition of leachate to a 12-foot column of MSW that achieves moisture content to 45% (Figure 3-2). The MSW has a starting density of 1000 lbs/yd^3. It can be noted that immediate settlement from liquid addition alone and 6" inches cover soil provides for 21% settlement and that liquids recirculation after this initial moisture addition allows for 40% settlement after a 2.5 year period.

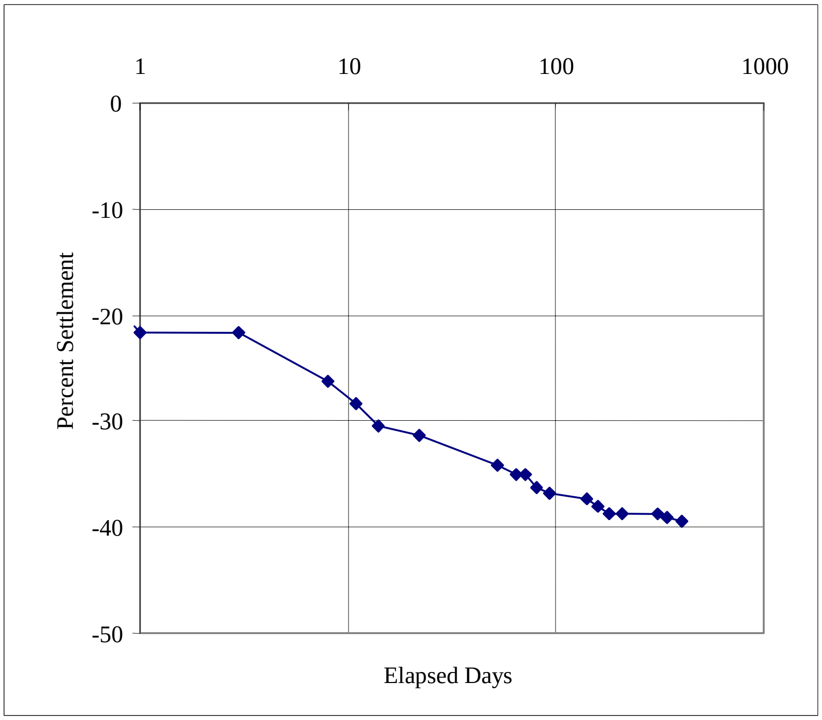


Figure 3-2. Liquids recirculation settlement results after moisture addition to field capacity of MSW *(Pohland, 1975)*

Figure 3-3 shows the effect of sludge cake and leachate on the increase in initial moisture content to field capacity with 6” of cover soil. Initial settlement was increased to 28%, and after 2.5 years of recirculation increases of settlement were up to 43%. The time it takes under anaerobic conditions to completely degrade most of the MSW and exhaust landfill gas was about 6 years under optimal conditions. The corresponding time frame for aerobic biodegradation may less than two years and a hybrid reactor requires somewhere in between the two.

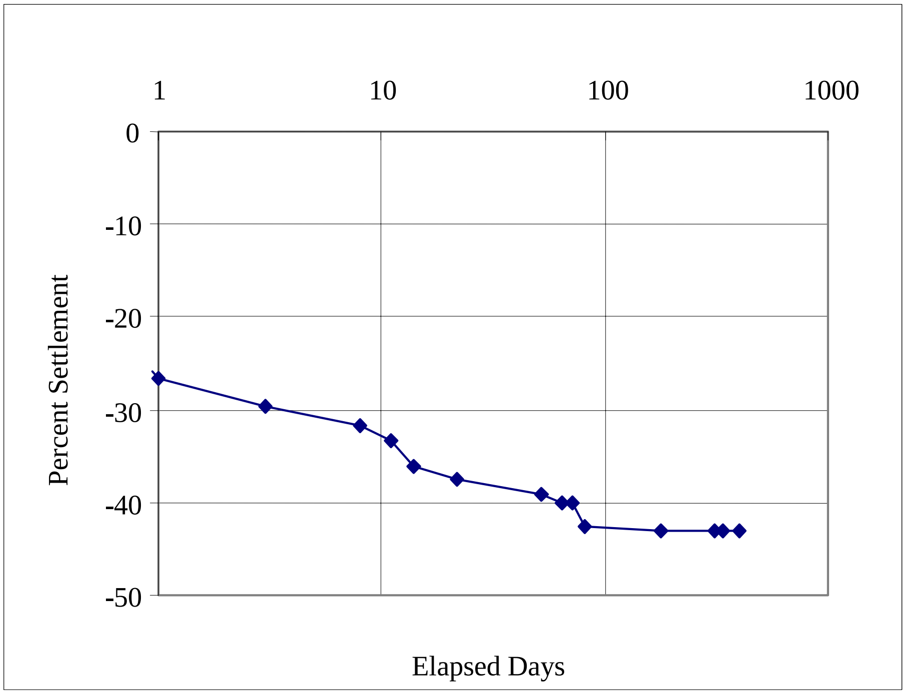


Figure 3-3. Liquids recirculation with sludge to increase moisture content to field capacity *(Pohland, 1975)*

Leachate quality results indicate that bioreactors accelerate the degradation of general organics (BOD and COD), and show a good correlation to degradation of hazardous organic constituents as well (VOCs). Hazardous metals also follow the same trend. Data from the Delaware Solid Waste Authority's Sandtown Landfill (at http://www.dswa.com/gen_links/VFTSandtown.htm) has historical leachate data for the last 21 years. The data indicate that when the landfill leachate BOD/COD ratios are <0.1, the VOCs and metals trend downward and are reduced to below drinking water standards in 15 years. This supports a stable nature of leachate from a degraded landfill and demonstrates that the source appears to no longer be a risk to HH&E.

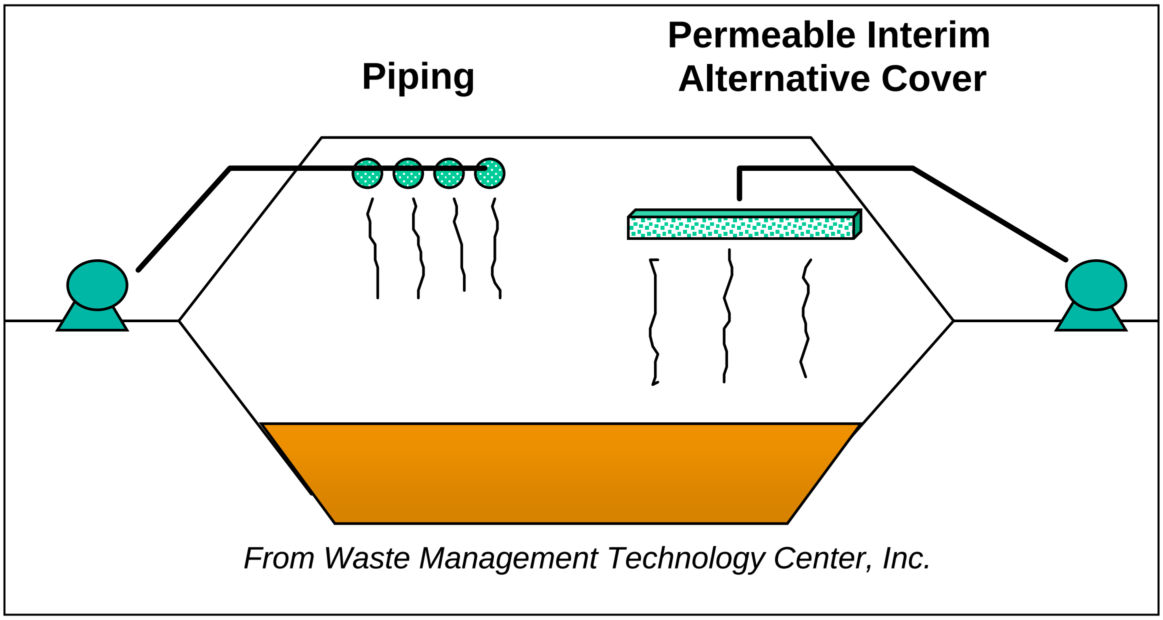
3.3 Bioreactor Recirculation Methods

The primary goals in the design of a liquids recirculation system are to provide

- a liquids distribution system that will allow uniform introduction of leachate or other liquids into the waste material;
- an environment that enhances biodegradation;
- a system that is compatible with normal landfill operations and material;
- a system that can survive normal landfill operations and settlement;
- a system that avoids odors;
- a system that minimizes operator attention; and
- a cost-effective system.

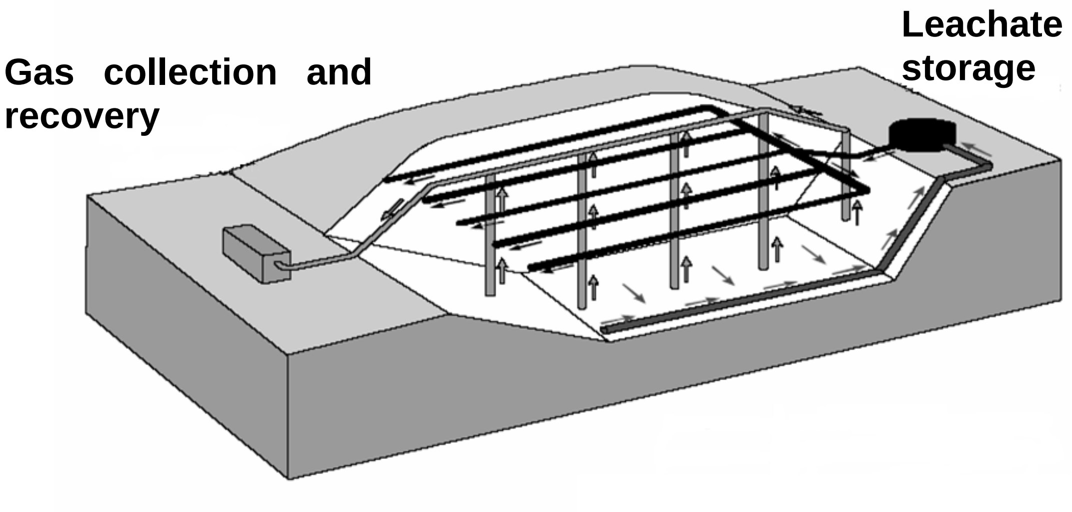
Depending on the type of bioreactor, leachate/water distribution can occur in one or more of the following ways.

- Spray application: This is perhaps the most rudimentary form of liquids recirculation. Spray application typically involves spraying leachate at the working face from a nozzled hose connected to tanker truck. While this method is effective for wetting the waste, workers' (landfill personnel and waste haulers) health exposure impacts must be considered.
- Vertical wells: Plastic perforated pipe is typically installed in a grid fashion into the waste fill. Leachate is pumped to the wells and is allowed to drain by gravity or is pressurized for distribution to the surrounding waste.
- Horizontal trenches: (See Figures 3-4 & 3-5) Perforated pipe is laid in permeable gravel packs within trenches. Leachate is pumped to the piping and either drains by gravity or under pressure to the surrounding waste. As landfill lifts are constructed, the preceding trench is put out of service and a new one is put into service.
- Surface ponds: Excavations are made at the landfill surface into the waste layer. Leachate is pumped into the open excavation and allowed to drain by gravity.
- Surface trenches: A series of long narrow trenches are dug at the landfill surface. Leachate is pumped into the open excavation and allowed to drain by gravity.



From Waste Management Technology Center, Inc.

Figure 3-4. Liquids addition using horizontal piping



From Waste Management Technology Center, Inc.

Figure 3-5. Leachate injection and gas recovery system

For gravity infiltration systems, water may be delivered via a distribution system (i.e. from an equalization tank) or directly from a tanker truck. Table 3-1 includes a variety of techniques available for applying liquids.

Table 3-1. Bioreactor process and applicable liquid addition methods

WASTE STABILIZATION PROCESS	TECHNOLOGY
Anaerobic Biostabilization	Vertical Wells Horizontal Trenches Spray Application Surface Ponds Surface Trenches
Anaerobic Biostabilization with Leachate Nitrification	Vertical Wells
Aerobic Biostabilization	Vertical Wells Horizontal Trenches
Aerobic/Anaerobic (Hybrid)	Horizontal Wells Semi-Aerobic Vacuum Induced Horizontal Wells

3.4 Landfill Hydraulics

3.4.1 Water budget

The total volume of leachate and other liquids that will be available daily for introduction into the waste mass may be determined by using a water budget approach. A global water budget first considers the current availability of leachate/water, recirculation, water consumption and generation (through decomposition) volumes. The water budget analysis can be used to determine the leachate collection removal system pumping rates and supplementary liquid volumes (i.e. make-up water) needed to attain the desired moisture content. This analysis, such as the HELP Model (discussed in section 3.5.3 below) can also help estimate the initial saturation (i.e. up to six months following system activation) and field capacity (up to five years of operation).

The water balance should consider the following site-specific parameters:

- Incoming waste moisture
- Preferential flow paths through the waste
- Even (not sporadic) moisture distribution
- Runoff
- Evapotranspiration
- Infiltration
- Waste field capacity
- Volume of waste receipt

3.4.2 Field Capacity

The field capacity, or the optimum waste degradation moisture content, is defined as that moisture content at which the maximum amount of liquid is held within the void spaces in the absence of gravity drainage.

3.4.3 HELP Model

The Hydrologic Evaluation of Landfill Performance (HELP) computer program (Schroeder, 1994) is a landfill hydrology model used when designing bioreactors. The HELP program is a quasi two-dimensional hydrologic model that simulates water movement through the landfill. The model may be used to estimate water balances under different design scenarios (ITRC ALT-2, 2004).

The amount of precipitation and leachate that travels through the waste mass can be approximated by the use of Darcy’s Law, where

$$Q = kiA$$

Q = flow rate (L3/T) into landfill
K = permeability of media (L/T)
i = hydraulic gradient (unitless)
A = cross-sectional area (L2)

The permeability of soil and fill materials is a measure of continuous voids. However, a reasonable approximation of the coefficient of permeability must be made, since heterogeneous materials, including cover materials, will yield different permeabilities. Differences in waste densities will also yield different permeabilities by as much as 2 orders of magnitude. The HELP Model employs a default waste permeability of 1x10-3 cm/sec, which is comparable to other hydraulic conductivities cited in literature. However, the designer should be aware that tall landfills with higher overburden stresses and higher waste densities may cause lower permeabilities.

The HELP Model may be used as a tool to assist in the design of a new bioreactor or evaluation of an existing leachate collection system (i.e. retrofit) and to estimate the quantity of leachate under different operational scenarios. The HELP Model uses three types of input data to estimate hydrologic conditions in landfills: climatological data (evapotranspiration, precipitation data, temperature, and solar radiation data), soil data (soil/material interfaces and properties for hydraulic conductivity, wilting point, field capacity, and porosity), and design data (landfill liner system cross-sections including vertical percolation layer, lateral drainage layer, soil layer and geomembrane liner). The HELP program estimates the amount of moisture that enters the bioreactor as precipitation (rain, snowmelt, etc.), which is then modeled as infiltration through the waste material. Water losses through evaporation and biological activity can be accounted for in the program. The total amounts of liquid added as recirculation and that fraction collected in the leachate collection system are then estimated by the model. To complete the water balance, additional quantities of moisture can be calculated that would be required to maintain the waste fill at the desired field capacity.

To summarize, the HELP model estimates the following for landfills and bioreactors:

- Quantity of leachate permeating through the waste fill
- Quantity of leachate removed by the leachate collection system
- Quantity of leachate potentially leaking through the bottom liner system
- Depth of hydrostatic head on the primary liner

3.5 Design Optimization

3.5.1 General Discussion

Liquids recirculation is not a new idea. Liquids recirculation has long been considered as a liquid management option in an effort to reduce leachate disposal costs or enhance gas production. What is new, however, is the concept of conducting full-scale bioreactor operations in such a way that continued performance under controlled conditions is optimized. This involves creating an environment favorable for microorganisms to thrive and enhance waste decomposition in the most efficient way possible. Accelerated decomposition of organic wastes is accomplished through controlled addition of liquids (and in some cases, air) to enhance microbial degradation of wastes. This process is contrary to traditional solid waste management practices whereby waste degradation was discouraged by minimizing the infiltration of liquids during the operational and post-closure phases of the landfill.

The number of existing full-scale bioreactors in the universe of municipal solid waste landfills is relatively small. Consequently, at the present time, there are data gaps and sparse field information available to facilitate effectively developing consistent performance and design criteria. There are currently several major demonstration projects underway in the United States in an effort to close the data gaps. The New River Regional Landfill (NRRL), managed by the

Florida Center for Solid and Hazardous Waste Management, is one such comprehensive demonstration project that is expected to help close data gaps.

One of the most important factors for optimal bioreactor performance is the uniform and continuous distribution of moisture within the waste mass. Particularly for retrofit landfills, this may not always be possible since prior operational practices and existing site characteristics may negate optimum performance goals (i.e. compaction densities, use of impermeable cover materials, etc.).

Given the existence of data gaps and sparse field information, many questions remain concerning performance optimization goals for bioreactors. The designer should consider the following:

- How do moisture requirements depend on site and geographical conditions and how do they change as stabilization of the waste mass proceeds?
- Does waste preprocessing provide any additional benefits?
- What nutrients may be needed, if any, to enhance the biodegradation process and when are they introduced?
- How can aerobic and anaerobic conditions be balanced jointly and independently in a hybrid bioreactor?
- What is the ideal compaction goal? What range of in-place waste densities are most conducive to bioreactor operations and yet maintain economic viability of airspace during the operational phase?
- Operationally, is it best to reintroduce leachate across a larger area with make-up liquids as needed to maintain field capacity or stagger liquids recirculation on one phase/cell at a time?

3.5.2 Factors affecting design optimization

The amount of leachate and makeup liquids that are introduced into a bioreactor (new or closed cell) in a controlled fashion without exceeding the regulatory requirement of liquid head on the primary liner system or causing operational problems, such as side seeps, will be largely determined by the following factors:

- The volume, composition, waste density and moisture content of the emplaced waste materials
- Climate, precipitation, and hydrology
- Liquids addition and management methods
- Landfill geometry, including interim height and final elevations
- Hydraulic capacity of the liquids recirculation system
- Design and configuration of overlapping cells with integrated liner and cover systems
- Placement and type of daily and intermediate cover materials

> The primary goal of the bioreactor landfill is to promote effective liquids recirculation so that enhanced degradation of wastes is maximized.

It will take approximately 1.75 inches of leachate/makeup water per foot of landfill thickness to raise the initial moisture content of waste at 25 percent to a field capacity of 40 percent or greater at an in-place density of

1200 lb/yd3. Approximately 25 to 50 gallons of additional moisture is needed per ton of disposed waste to attain field capacity. In many cases, leachate alone will not be a sufficient source of liquids in order to maintain the desired moisture content. Other supplementary liquids should be considered, including landfill gas condensate, storm water and surface water.

In practice, the high end of field capacity should not be attained in the field due to slope stability concerns. In fact, water content should not exceed 40 percent water by weight due to the potential for decreased stability with over saturation.

The heterogeneity of waste materials in the landfill and the type of daily and intermediate covers will restrict the uniform distribution of leachate and makeup water. Low impermeable soils can result in ponding and perching of leachate in the waste area, preventing it from draining to the waste below. Therefore, alternate materials and practices should be considered to promote free flow of leachate between lifts.

For any bioreactor type, optimization of the design should consider the following, where applicable:

- Techniques to measure hydrostatic head on liner system and use of appropriate sensors. Hydrostatic head can be determined by differential pressure measurements, such as transducers
- Type of liner system used in the bioreactor. For example, the choice between a double liner system, with provisions for leak detection monitoring, as opposed to a single composite, which may not have a secondary leachate collection system. Leachate compatibility tests may have to be performed on the liner material if equivalent data does not exist.
- Availability of data for specific waste types and properties, in order to accurately conduct slope stability analyses
- Accurate assessment of geotechnical considerations due to changes in static and pseudostatic forces of waste mass throughout life of bioreactor
- Recirculation of most of the leachate generated at the facility
- Uniform distribution of leachate throughout the waste mass, to avoid channeling and ponding of liquids within the landfill
- Anticipation of consolidation and differential settlement; wells should be kept away from the exposed edges of the landfill
- Ability to monitor effectiveness of distribution system in terms of liquid delivery to the appropriate location as well as uniform liquid delivery
- Consideration of multi-liquid delivery systems (vertical and horizontal wells) to improve efficiency
- Control leachate outbreaks due to overpumping or perching of leachate
- Optimization of landfill gas control (i.e. avoid flooding of gas collection systems)
- Overcompaction of waste, resulting in higher in-place densities, may impede liquids recirculation.

Low permeability soils should not be used as daily or intermediate cover since the application of these materials can result in internal ponding and lateral deflection of added liquids and the potential generation of seeps on side slopes. The use of alternate cover materials is strongly encouraged in order to promote free flow during the liquids recirculation process.

Permeable alternative daily and intermediate covers are used to promote the passage of liquid to saturate the waste and allow the movement of liquid down into the collection system. The method of controlling landfill leachate seeps should be specified (installation of vertical sand drains, etc.). Addition of nutrients (the role of key nutrients, nitrogen and phosphorus, is well understood but quantities and method of distribution must be evaluated).

Design drawings showing all plan views and profiles of the liquids recirculation system that will uniformly distribute liquids throughout the waste mass should be prepared. In the case of horizontal piping systems, more than one level of distribution piping may be required (i.e. intermediate and high-level elevations) depending on the specific characteristics of the landfill. A lift of waste should be placed on the recirculation system prior to operation since below grade discharges are essential to minimize odor migration and surface evaporation losses.

3.6 Design Components

3.6.1 Liners

Regulations allow for flexibility for use of single composite liners, single non-composite mixed composite liners, and double liner systems with leak detection systems. Although the USEPA RD&D rule allows for liquids recirculation on alternative liners, most states require standard composite liner systems. Many in the waste industry understand that virtually every liner will leak some amount given construction imperfections and material fatigue with time. They appreciate, even if more expensive to construct, the redundancy in of composite liner systems as adding an extra level of protectiveness and liability management. Recirculation on primary PVC liners should be discouraged since these liners tend to lose plasticity over time (Koerner et al 1988). Compatibility testing may need to be performed depending on the type of liner system materials selected.

3.6.2 Leachate Collection and Removal Systems:

Leachate collection systems for landfills and bioreactor systems must be designed to efficiently collect, remove, and manage leachate. The Federal and most State regulations require that the height of leachate head on the primary liner be less than 30 cm (1 foot) to minimize the threat of groundwater contamination. Evaluation of site specific leachate characteristics to minimize clogging from particulates (TS, TDS, TSS), biological agents (COD, BOD, TOC) and precipitates should be conducted to ensure the efficacy of the design.

As leachate is moving through the waste mass at sufficient quantities for field capacity to be maintained, the leachate collection system must have sufficient drainage capability. Most state regulations require a minimum hydraulic conductivity of 0.01 cm/sec for the drainage media in order to adequately convey leachate to the piping distribution system. This value may be too low for sufficient drainage in liquids recirculation systems. As such, the leachate collection media should have a permeability of greater than 1.0 cm/sec.

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. Retrofitting a bioreactor on an existing landfill should evaluate existing leachate collection design since repair, removal or replacement of the system is cost prohibitive. Leachate collection systems in conventional landfills that have incorporated geotextiles (as a pipe blanket) or sand as a drainage media are likely to experience a decrease in hydraulic conductivities between one and two orders of magnitude less during the operational life of the facility. Likewise, more organic material can be expected to move through the landfill and into the drainage system during the early bioreactor stages when the pore space is much higher in the waste mass than at later stages, resulting in a much higher potential to plug the drainage system earlier in the process. Materials, such as insoluble aggregate, with increased and more sustainable flow capacity are preferable to finer material such as sand, which can promote clogging of collection pipes. A perforated pipe network within a suitable material accompanied by a geonet is recommended. Also wrapping geotextile fabric around collection pipes to prevent fouling must be avoided. Furthermore, the designer should establish a suitable flow capacity.

The pipe design should include an evaluation of flow capacity, spacing, and crush strength. Crushing of pipes depends on the unit weight of the waste mass; if the unit weight increases, the load increases, and the factor of safety becomes lower. The design should also ensure that pipe connections are secured and not be prone to deformations during biostabilization, compaction, and subsidence.

For example a perforated pipe network could be embedded in V-shaped trenches spaced at regular intervals (i.e. 100 foot intervals) and sloped to maintain performance requirements (typically one foot of head). Drainage material could be used in the V-shaped trenches. The collection pipes should be designed to convey leachate into the perimeter manholes by gravity and without impediment.

The use of a geosynthetic geonet possessing a high transmissivity value must also be considered. Using a geonet in conjunction with the stone drainage layer will enhance the performance of the collection system and control the head on liner during high flow conditions. However, the filter fabric on the geonet should be evaluated for potential clogging. Restrict the use of geotextiles or sand in the drainage layer, which can promote clogging. Specify a sufficient number of cleanouts to facilitate ease of cleaning since plugging of pipes may occur during initial bioreactor operations due to higher organic loading when void spaces within waste are sufficiently large. The collection line should extend from one end to the other so that the pipe is accessible for cleaning or flushing. To prevent clogging, pipe junctions within the landfill should be minimized. Additionally, long runs of pipe and small diameter pipe should be avoided.

Leachate head level sensing devices should be installed on the liner system at the time of construction to facilitate the monitoring and to provide data demonstrating that the head is less than 30 cm. The leachate collection and removal system should have appropriately located valves; if the sensing devices indicate an exceedance in head, leachate flow is reduced until the head on the liner subsides to less than 30 cm.

3.6.3 Liquid circulation systems

An optimum leachate circulation system would be capable of effectively saturating the waste and then maintaining the waste at field capacity. Leachate injection line locations and spacing should be evaluated by a professional engineer to ensure uniformity of liquid delivery system. The design of a piping network should consider the trench size and spacing, and the injection pressure and schedule. Also, liquid injection lines and wells should not be placed too near the edge of the landfill to jeopardize slope stability or initiate seeps. The system should have the ability to control flow in order to minimize local pore pressures, piezometric head, and seepage forces. Access to frequent leachate collection and removal system cleaning should be designed in light of the fact that increased leachate flow rates may increase the potential for clogging.

For efficient bioreactor operations, horizontal and vertical injection systems may provide the most reliable means of recirculating leachate throughout the waste mass. Internal moisture distribution is an important design consideration. Constructing such systems within the waste mass may improve moisture distribution over that achieved by trickling liquids down through the waste from the top of the waste mass. This may help to avoid mounding and the problems associated with preferential pathways or blockages developing around denser material. The number and location of wells or trenches required for the even distribution of leachate depends on the hydrodynamics of liquid flow through a landfill. To that end, computer software developed by the U.S. Geological Survey, named SUTRA (Saturated and Unsaturated Transport Model), was developed to simulate leachate flow from vertical and horizontal wells. Further design guidance on this subject is available in Reinhart and Townsend (1999).

3.6.3.1 Gravity Infiltration Systems

Gravity infiltration systems are the most simplistic approach used for introducing leachate at the working face. This is done with tanker trucks fitted with spray bars. The drawback to this method is that liquid distribution tends to be uneven and sporadic. Odor problems could occur with liquids recirculation at the working face. Surface impoundments and open infiltration trenches are also used within operational areas. Typical percolation rates for surface leachate applications range from 0.2 to 0.5 gpd/ft^2; however, team members have experienced seepages above 0.3 gpd/ft^2. Operation of these systems is weather dependent. Water addition should be done carefully and slowly since it could cause problems with leachate seeps and stability. The team cautions owners and operators that this range is highly site dependent and should be used with caution.

Below surface systems include liquid bed distribution systems and recharge wells. As these systems are not exposed to the atmosphere, they may result in reduction of odors and can be used in all weather conditions. These systems are susceptible to biological fouling, which can be minimized by using pervious materials and avoiding geotextiles.

Vertical wells consist of perforated pipe backfilled with gravel or other materials of suitable porosity and hydraulic conductivity (i.e. shredded tires). Vertical wells help promote liquids recirculation through layers of daily/intermediate cover and heterogeneous materials. These kinds of wells withstand settlement forces better than horizontal wells; however, they are prone to biological plugging. The design should account for flushing techniques; otherwise plugged wells may be abandoned in favor of a new well point. Due to significant down drag forces, vertical wells should be terminated at least 10 to 15 feet above the baseliner to avoid damage to the liner system.

Liquid bed distribution systems consist of perforated pipe in gravel backfilled trenches that are sloped and can be distributed in active and closed sections of the landfill. Leachate is pumped into the trenches or discharged by tanker trucks.

3.6.3.2 Injection systems

Vertical and horizontal piping systems may deliver leachate under pressure so that uniform distribution occurs in the proximity of the pipe. Spacing of the pipes is designed such that the injection rate does not exceed the hydraulic capacity of the wetted area. Injection systems are advantageous in that higher injection pressures are used to overcome fouling and encrustation in the drainage media surrounding the pipe.

3.6.4 Landfill Gas Control and Recovery Systems

Liquids recirculation in an anaerobic bioreactor will significantly increase the rate of waste decomposition and the rate of LFG generation. The time dependency of the peak availability of methane (the most significant LFG component relative to gas use) is paramount to successful landfill gas recovery and reuse projects.

Through full-scale liquids recirculation, landfill gas production can be expected to increase by 2 to 4 times the production rate for a typical landfill in the northeast U.S.

Gas production potential within a dry landfill and a landfill bioreactor is volumetrically the same. However, higher gas generation rates over shorter timeframes are expected for bioreactor landfills (a traditional Subtitle D landfill generates 30% of total LFG by time of closure while a bioreactor landfill can generate over 80% during the same period). Therefore, the design should consider the potential for LFG collection and recovery due to shorter timeframe. The gas venting system must be sized to handle the increased gas production rates. The design might consider early installation of larger collection pipes and blowers. Liquids recirculation should be initiated only when the gas venting system is constructed and operating.

Bioreactor landfills should be designed and constructed to allow gas recovery coincident with the beginning of landfill operation.

Gas collection should be designed to work with leachate collection and recirculation systems. In most traditional landfill designs, gas collection is not initiated until after the final landfill cover is constructed. However, landfill gas management does not necessarily control odors, such as those generated at the working face. Working face odors must be controlled using other management techniques.

3.6.4.1 Gas Systems Modeling

Gas collection systems exist in two primary types: passive and active systems. Passive systems typically involve the use of wells with vent pipes or permeable gravel trenches in and around the landfill. Gas travels through the path of least resistance into the vent pipes or trenches below the final cover system and is discharged passively into the atmosphere. Such discharge is allowable only where emissions restriction would not be exceeded. Active systems involve the extraction of gas by means of an induced draft system. This system consists of a series of gas extraction wells and collection piping, which often are connected to a flare for combustion (or other gas destruction method) or is recovered as fuel, as mentioned above.

Gas production rates at landfills vary significantly, depending on the waste types and moisture content of the wastes. As is the case with leachate, the quality and quantity of landfill gas vary with time. There are a number of gas emission models available to evaluate the quality and quantity of landfill gas. Among these is the USEPA, (EPA 2005) Landfill Gas Emissions Model (LandGEM) V 3.02 that uses AP-42 emission factors. This model predicts gas generation flows based upon site specific information including waste tonnage placement and inflow, waste types, volumetric capacity and life expectancy.

The gas venting system must be sized to handle peak gas generation rates during the active bioreactor operation phase. To design a landfill gas system, computer models based on the Darcy-Weisbach equation are used to determine head losses in the system. One such model is the KYGAS Model, developed by Dr. Don J. Wood and Dr. James E. Funk of the University of Kentucky.

The ITRC ALT team recommends that landfill projects, and especially bioreactors, should plan for gas management strategies early in the design of the project. This improves the integration of LFG regulatory requirements with other landfill regulatory requirements such as the following:

<u>RCRA Subtitle D:</u>

- Explosive gases must be maintained below 100% LEL (or other appropriate regulatory limits) at the point of compliance, typically at the property boundary
- Explosive gases must be maintained below 25% LEL within landfill structures (excluding gas control and recovery components)
- LFG impacts to groundwater
- LFG impact on air emissions
- LFG and the types of covers:
    - AFC's may allow gas to migrate to the atmosphere yet still be in compliance with local and/or applicable federal air emission requirements. (See ALT-2, 2003).
    - Infiltration of water can inject air into the bioreactor process while liquid infiltration through the soil can potentially treat the methane prior to release to the atmosphere.
    - Conventional covers may more easily facilitate gas entrapment and collection for beneficial reuse and maintenance of local air quality and emission standards.
- Full utilization of landfill gas management may reduce/mitigate impacts to groundwater. The state of California research indicates that 75-80% of the landfill groundwater impacts are

associated with landfill gas as opposed to landfill/liner release of leachate or liquids. (Peter Fuller, Personal communication, 2005)

Timing: Operational:

- Post-Closure Care may be accelerated based on the increased rate of LFG generation. The potentially saved cost of prolonged Post-Closure Care may offset the cost of the capitol required to design, construct, and operate a LFG management system.
- Siting a facility is important in establishing a customer base for the captured gas or permitting costs for flaring gas. If the plant uses the energy from the captured gas, on-site impacts need to be addressed whereas if an offsite vendor uses the gas for energy generation the off site population should be consulted prior to the final design decision.

3.7 Geotechnical Considerations

Waste stability is a critical component of bioreactor design. Because bioreactors introduce high volumes of liquid and air (aerobic systems), the fundamental question becomes whether or not the operation of a bioreactor will cause a destabilization of the waste mass from a slope stability perspective. The addition of significant amounts of liquids increases the total weight of the waste mass and affects the structural characteristics of the waste mass.

The addition of liquids adds weight to the waste mass but does not contribute to increased shear strength. A dry waste mass can exhibit high strengths as evidenced by stable modern landfills with fill heights of up to 300 feet and slopes steeper than 3:1. During liquids recirculation, pore pressures and fluid volumes decrease and waste shear strength changes should be accounted for in the design. Selected shear strength values are needed for the waste, liner system interfaces, and subgrade. These values are significant for calculating the factor of safety against failure since they ultimately represent the stabilizing forces of the landfill.

A wet landfill can result in as much as a 50% increase in the total unit weight of the waste and the unit weights increase with height (i.e. doubles in the first 150 feet). As such, the overburden weight or height of the landfill may be the limiting factor. The resulting changes in waste density may affect seismic and other stability requirements which should be fully evaluated from subgrade preparation through final cover placement. The increased density of the waste through the decomposition process and settlement may result in the waste mass becoming more unstable with steeper slopes, thereby reducing the designed safety factor. If reuse of the “recovered” landfill airspace is being considered, the designer should consider how placement of new waste on top of a stabilized waste mass would also affect landfill stability.

The analysis should also consider density changes and settlement of waste mass from compaction and decomposition. In addition, the analysis should evaluate the impacts of liquids recirculation on the landfill subbase, liner system, leachate collection/removal system, and waste mass from a stability perspective so that these systems are not compromised by the increase in normal loading resulting from higher mass densities. The designer should also evaluate how changes in waste mass, hydraulic head and pore water pressure (from liquids recirculation) affect the design parameters. Increased differential settlement must be evaluated in the design for potential impact on the leachate collection system, active gas collection system and final cover system. Some geometries (bottom grades, side slopes of cell excavation, interim and final grades) used for dry landfills may not work for wet or bioreactor landfills because of the potential for landfill instability caused by water addition.

The designer should also conduct a sensitivity analysis by inputting different waste strengths and interface strengths to see how the factor of safety changes. From the analysis, certain safety factors may need to be addressed in design and operation to prevent landfill failure. The design must try to control the hydraulic head/pore water pressure. Pore water pressures remain high during active bioreactors for long periods of time. If pore pressure increases, the strength of waste decreases, and may cause instability resulting in slope failures. Pore pressures can also be increased by air injection.

3.7.1 Stability Analysis

For both static and seismic cases, critical cross-sections are delineated within the landfill that represent in the lowest factor of safety. The designer must evaluate whether the calculated factors of safety at the critical cross-sections satisfies regulatory requirements. If not, additional design and/or construction requirements may be necessary. A plan must be developed for periodically re-evaluating landfill stability, as applicable, during bioreactor operation, closure, and Post-Closure Care.

3.7.2 Bioreactor slope stability

While undertaking a slope stability analysis for a bioreactor landfill, the designer should consider the following:

- Increased weight of wet waste compared to the weight of conventional waste.
- Evaluation of bioreactor foundation and liner system: The most critical material interfaces are analyzed. Materials used as part of the finite slope program include unit weight, friction angle, and cohesion. In the static case, several cases should be examined where material properties varied. Since the critical failure surface in each case passes through the waste, any variation in the friction angle of MSW results in a variation in the factor of safety. Therefore, the selection of a friction angle for MSW in bioreactors should be conservative.
- Seepage of leachate in side slopes could present potential veneer stability failures. This may be difficult to predict beforehand but may serve as a “preliminary” warning during the operation phase.
- As discussed above, the use of relatively low permeability daily cover materials may result in perched leachate conditions. This can result in a build-up of pore water pressure within an isolated zone. Therefore, planar surfaces through these zones should be analyzed.
- Gas pressure within a landfill generally is usually not a consideration in a slope stability analysis. However, when the waste is saturated, landfill gas may contribute to pore pressures as a result of the gas/pore water phase.

3.7.3 Subgrade settlement analysis

Geotechnical analysis for a bioreactor should also include subgrade settlement. As with conventional landfills, subgrade settlements resulting from bioreactor operations may be estimated using the Schmertmann strain method, or other appropriate methods, based on available subsurface information consisting of boring logs and cross-sections. Long-term settlements for landfill subgrades are generally predicted from time equal zero (instantaneous) to time equal 25 years (including creep).

3.7.4 Methods for predicting waste settlement

There are several methods available to estimate waste settlement in a traditional landfill (Sowers Method, Power Creep Law, Gibson and Lo Model) See Waste Management & Research Volume 17, Issue 5, Page 347 (http://www.blackwell-synergy.com/doi/abs/10.1034/j.1399-3070.1999.00059.x). However, these methods currently do not provide adjustments for liquids recirculation in bioreactor landfills. Notwithstanding this, these settlement models can be used to approximate long-term settlement in bioreactors provided that input parameters are adjusted for the organic content of the waste, moisture conditions, and compaction practices. An EPA document (in progress) is currently under development that will provide guidance on predicting settlement rates resulting from bioreactor operations.

4.0 BIOREACTOR CONSTRUCTION

Following the design and successful permitting of a bioreactor project, construction of a bioreactor should include construction methods quality assurance and quality control measures to ensure compliance with the approved designs. Since bioreactor landfills must operate in conformance to regulations that apply to active landfills, construction procedures for bioreactors must be as rigorous as those used for any new cell construction. The permittee proposing to construct the bioreactor must be responsible for ensuring that all construction-related activities are performed by qualified personnel.

The approach to a complete bioreactor landfill design for a new landfill is to consider construction details during the initial design and permitting process for a new landfill. However, in many cases, bioreactor components are retrofitted into an operational landfill where construction of the landfill infrastructure has already occurred. New or retrofitted bioreactor landfills, (i.e. anaerobic, aerobic, hybrid) are constructed in much the same way as conventional RCRA Subtitle D landfills since both types require bottom liners, gas recovery, and leachate collection and recovery systems. Therefore, construction issues are similar for full-scale and retrofit bioreactors since the landfill infrastructure and its related components must satisfy RCRA Subtitle D and state regulations.

4.1 Construction Quality Assurance and Construction Quality Control Plan

> Construction Quality Assurance and Construction Quality Control plans, along with state-of-the-art designs, are critically important factors in successful bioreactor construction projects.

A Construction Quality Assurance and Construction Quality Control (CQA/CQC) plan should be included as a part of the design submission during the permitting process. The CQA/CQC Plan should outline the observations and tests to be used to ensure that construction of the bioreactor meets or exceeds all design criteria, plans, and specifications.

The process of verifying and documenting conformance with the very specific and detailed requirements in bioreactor design documents is intended to be consistent with the federal regulatory requirements as contained in 40 CFR 258.60(c). These regulations include requirements for construction and refer to the required documents as CQA plans and the persons responsible for verifying and certifying conformance with approved plans as CQA personnel, CQA officers, and registered professional engineers. These regulations are applicable for the construction of bioreactors as well. For simplicity of reference in this manual, the terms CQA or CQA officer are used. Any conflict between the way these and related terms are used by State regulatory agencies or others interested in bioreactors and the way the same terms are used in this regulatory guidance manual is unintended. This portion of the guidance manual emphasizes the importance of verifying and documenting conformance with approved bioreactor design documents.

The CQA/CQC Plan should also specify the responsibilities of all participating parties in the project. Figure 4.1 presents a typical depiction of what the quality assurance/quality control QA/QC hierarchy will look like for a bioreactor construction project. In this example, the functions are generally separated once the construction contractor assumes overall responsibilities during construction activities.

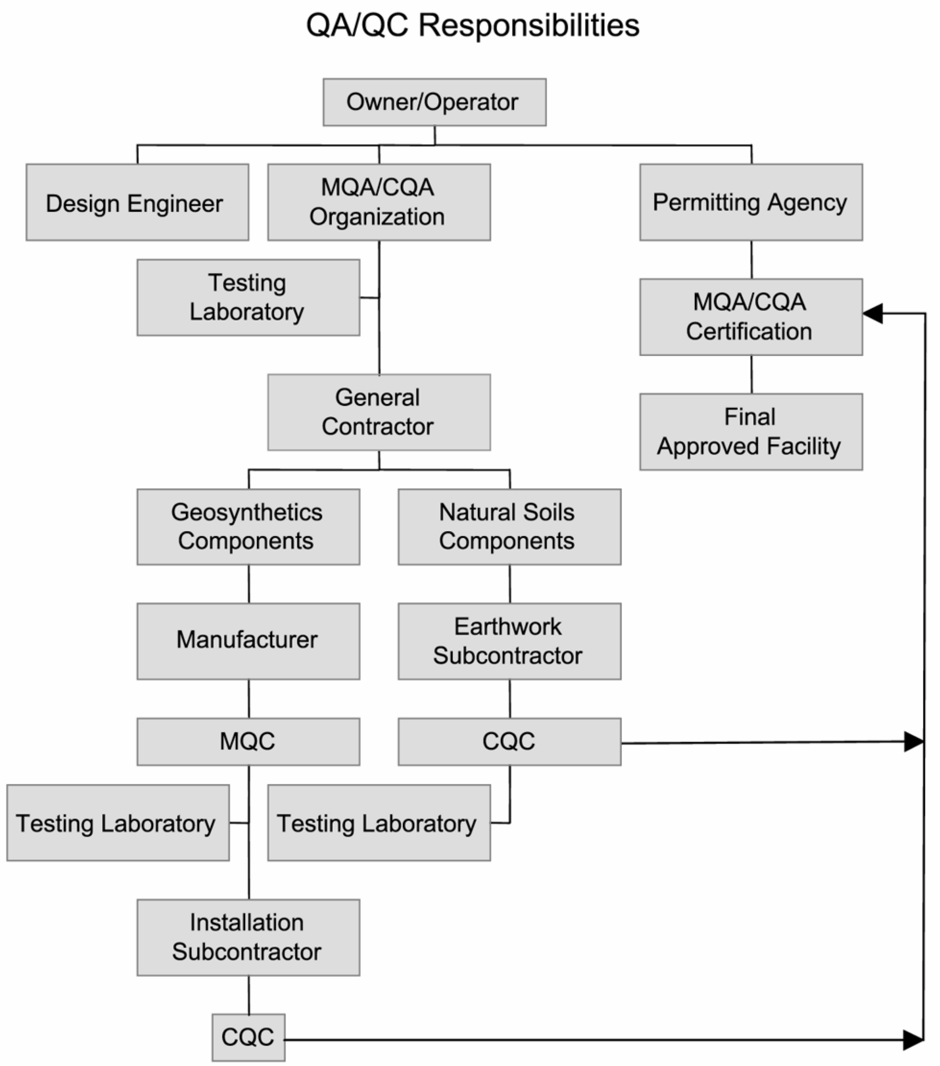


Figure 4-1. QA/QC responsibilities

Although the actual QA/QC hierarchy for a specific bioreactor construction project may vary, the QC parties report to the owner, whereas the QA inspector is retained by the owner but is independent and serves the "eyes and ears" for the regulatory agency responsible for issuing the bioreactor construction permit.

4.2 Construction Quality Assurance and Quality Control Procedures

To ensure with a reasonable degree of certainty that the construction of a bioreactor system meets the design specification, a CQA plan is essential. The CQA plan, which incorporates the concepts of quality assurance and quality control, also affords a formal basis for certifying that the bioreactor was constructed according to design. As defined below by USEPA, in "Solid Waste Disposal Facility Criteria Technical Manual" (November 1993, EPA530-R-93-017):

> "Construction Quality Assurance consists of a planned series of observations and tests to ensure that the final product meets project specifications. CQA plans, specifications, observations, and tests are used to provide quantitative criteria with which to accept the final product."

CQA is an integrated system of management activities involving planning, implementation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected.

> "Construction Quality Control is an on-going process of measuring and controlling the characteristics of the product that is employed by the manufacturer of materials and by the contractor installing materials at the site."

A sampling program should be implemented as part of the CQA plan, for all construction activities, in order to ensure, at a minimum, that construction materials and operations meet the project requirements. The sampling program should be based upon statistical sampling techniques and should establish and specify criteria for acceptance or rejection of materials and operation. Construction of a bioreactor, involves both natural materials and geosynthetics so that quality control procedures differ among media types. The purpose of any CQA test or observation is to compare the material used, or the work actually performed, with the specified material or workmanship. The design specifications for the bioreactor establish the parameters that will be evaluated for the acceptance of the materials and work. Furthermore, testing of the materials prior to (for characterization) or during construction will determine whether the properties, composition, and /or performance of the material(s) or installed components are within the limits specified in the design.

Observations and testing are important and necessary CQA activities throughout all phases of the bioreactor construction. Observation of all component materials as they are delivered to the construction site and installed in proper sequence provides compliance with design specifications and procedures. Accordingly, the CQA plan must be developed by the facility owner/operator and approved by appropriate regulatory agencies prior to the commencement of any construction activities.

The plan should include a CQA hierarchy and structure approved by the facility owner/operator and the appropriate regulatory agencies prior to the commencement of any construction activities at the facility. The hierarchy and structure should list the "parties" involved in CQA activities. The "parties" list should detail the affiliation of all the personnel involved in CQA of the bioreactor. The CQA plan also should clearly outline the duties of CQA personnel. Finally, but most importantly, the documentation procedures also should be outlined in the CQA plan. The effectiveness of the CQA plan depends largely on the recognition of construction activities that should be monitored and on assigning responsibilities for monitoring each activity. This is effectively accomplished and verified by the documentation of QC/QA activities.

Manufacturing Quality Control (MQC) specifications are manufacturer-controlled so that resins and additives of products meet vendor certified values. MQC is performed by the manufacturer to ensure that product meet specifications Manufacturing Quality Assurance (MQA) specifications are consultant-controlled to determine if the manufacturer is in compliance with the product specifications. CQC specifications are contractor/installer controlled and include measures undertaken by the contractor to determine compliance with plans/specifications. This includes product conformance testing and ensures that correct installation procedures are used. CQA specifications are consultant controlled on behalf of the owner and permitting agency to determine conformity with design and compliance with permit. Natural soils require CQC/CQA and geosynthetics require MQC/MQA and CQC/CQA. Both media require knowledge of applicable test methods (e.g. American Society of Testing & Materials, Groundwater Research Institute, Department of Transportation, etc.) and sampling strategies of items used in the work.

MQA and CQA activities are performed independently of the MQC and CQC parties to provide a "check" on construction materials and installation procedures performed by the contractor. Each product and test specification should reference the current standard in effect for that product and test method.

Prior to construction activities, a preconstruction meeting is held to identify the field personnel of all parties involved and answer questions (design engineer, QA/QC personnel, contractor, installers, and regulatory agency). Thereafter, progress meetings should be scheduled at regular intervals. Preconstruction and progress meetings are quality management tools whose importance cannot be overemphasized; progress meetings are typically held weekly or more frequently if desired by the QA party.

4.3 Construction Details

Construction details for a bioreactor project should follow the Engineer's Project Specifications and installation sequence as provided for in the design. Where applicable, the CQA/CQC Plan should address all if the following aspects of construction. Best available engineering construction practices should be employed for all phases of the bioreactor construction. Construction of a bioreactor landfill involves the following major construction phases:

- Site Preparation
- Design sensitivity of key operational parameters
- Earthwork

- Trenching, backfilling and compaction
- Erosion and sediment control
- Grading
- Paving and surfacing (for access roads and appurtenant structures)

4.4 Recordkeeping

Construction documentation might include daily inspection reports, daily summary reports, inspections sheets, problem identification and corrective measures reports, record drawings, field documentation and certification sign-off sheets. All laboratory reports and field testing results should be reviewed, signed, and dated by a Quality Control inspector. A bound log book should be maintained at the site during the active construction phase and could include the following:

- A daily summary report should be prepared by the CQA officer, or under the direct supervision of the CQA officer, during each day of activity. The report should contain, at a minimum:

    - The date
    - A summary of the weather conditions
    - A summary of locations where construction is occurring
    - Equipment and personnel on the project
    - A summary of any meetings held and attendees
    - A description of all materials used and references or results of testing and documentation
    - The calibration and recalibration of test equipment
    - The daily inspection report from each inspector

- Daily Inspection Reports should be completed containing the following information:

    1. The location
    2. The type of inspection
    3. The procedure used
    4. Test data
    5. The results of the activity
    6. Personnel involved in the inspection and sampling activities
    7. The signature of the inspector

- Photographs may be used as tools to document the progress and acceptability of the work and may be incorporated into the daily summary report, daily inspection report, and an acceptance report. Each photo should be identified with the following information:

    1. The date, time, and location of photograph
    2. The name of photographer
    3. The signature of photographer

4.5 Construction Certification

The construction Certification Report should include as-built drawings signed, dated, and sealed by a Professional Engineer licensed in the state (state certification requirements may vary) of the bioreactor project. All designs should be prepared by, or under the supervision of a professional engineer. The report should also certify that the bioreactor was constructed in accordance with the approved design and that all the required testing was accomplished in accordance with applicable standards. The record drawings should include survey data that show bottom and top elevations of a bioreactor component and the plan dimensions of the components. Separate drawings are appended to indicate cross-sections and special features. The report should also include all of the daily inspection reports, MQA (Manufacturing Quality Assurance) /CQA (Construction Quality Control) engineer's reports, inspection sheets, laboratory test results, internal memorandums resolving areas of conflict, and any work change orders approved by the certifying engineer. The certification report, including any inspection data sheets, should be retained at the facility for future reference.

5.0 BIOREACTOR OPERATION

Bioreactors fall into two major categories: "As built" bioreactors that are constructed during the fill sequence, and "retrofit" bioreactors that are retrofitted into an existing cell at or are near final grade.

This section discusses the key operating components. Specialized operating components often contain proprietary information. Patents exist for several bioreactor technologies as well as advanced collection and infiltration systems.

5.1 Waste Filling and Compaction

Typical compaction and filling in conventional landfills is similar, but may not be optimal, for bioreactors. Fill sequence and types of interim cover may be important. Thus, attention must be paid to compacting and covering practices to provide adequate permeability of the waste material and facilitate the distribution of liquids, thereby enhancing the biodegradation processes. A site geotechnical analysis will establish requirements for interim stability.

Waste filling procedures should homogenize the waste to the maximum extent practicable help achieve field capacity throughout the landfill. Optimal operation includes subjecting all of the waste to recirculated liquids and minimizing preferential flow paths. Waste preprocessing (tromelling, shredding) may be conducive to efficient bioreactor operations, but the cost should be considered against the overall economics of the bioreactor project.

The landfill should be operated in such a manner that it does not contain appreciable amounts of tires, yard waste, lumber, tree trunks and limbs, bulky waste/white goods; sludge, ash, household hazardous wastes, or shingles. These wastes should be intercepted and directed on-site or off-site for processing and/or disposal by means other than landfilling.

- To excavation must be avoided; if left unbuttressed, this could create high stress and may potentially cause a slide.
- Filling waste on steep grades must be avoided.
- On-site roads and cover soil may contribute to instability, thus requiring more care with design.
- Potential for landfill fires through temperature control (esp. aerobic systems) as well as carbon monoxide monitoring must be minimized.

As previously stated, permeable material such as select inert C&D waste (excluding reactive material, e.g. pulverized sheetrock), foams, tarps, etc should be used as daily cover that will not block or hinder movement of recirculated leachate and moisture throughout the waste mass. Operators should strip daily cover for this technology to be successful. After stripping a track hoe should be used to dig windows in the trash. These windows should be filled with tire chips, glass cullet, C&D, or gravel in order to create channels for liquid to move downward.

5.2 Aeration (For Aerobic and Aerobic-Anaerobic Bioreactors)

As Built

Aerobic conditions are established by injecting air into one or more of the most recently placed waste lifts. While it is preferred that aeration is limited to the top ten feet, as many as three lifts, or thirty feet, may be aerated at a time. The number of lifts being aerated is dependent on the operations fill rate. The blower used for aeration should be capable of delivering from 0.01 to 0.06 standard cubic feet per minute per bank cubic yard (bcy) of waste (scfm/bcy). A higher aeration rate (up to 0.06 scfm/bcy) is acceptable but evaporative loss of water could make temperature management more difficult and adversely impact the biodegradation rates. Typically horizontal piping is laid in the working face on 60 ft centers. There have been instances of pulling oxygen through a cover system into a bioreactor landfill. Even though this allows all emission from a landfill to be captured it is prohibitively costly at a full scale.

Retrofit

Vertical wells are drilled either in clusters or as individual units. In addition, well spacing is variable and is generally recommended based on an evaluation of the radius of well influence. The clustered wells are completed at varying depths to get top to bottom aeration.

5.2.1 Length of Aeration

Team experience indicates that optimum aeration time varies from 1-3 months and is dependent on the following factors:

- Food content of the waste
- Moisture content of the incoming waste
- Ambient air temperature and the blower air temperature
- Density, saturation, and permeability
- Evaporative water losses

Degradation of fresh wastes placed in an as-built bioreactor proceeds at a much faster rate (i.e. fractionally) than "aged" wastes in a retrofit bioreactor.

Blowers can increase the exhaust air temperature by about 30º F due to adiabatic expansion. Summer aeration cycles may be shortened unless the moisture content of the waste is higher in the summer than has been observed in the winter. Gas sampling can be used as a monitoring tool to determine the oxygen content in the aerated lift.

Aerobic – retrofit bioreactors

Length of aeration is typically greater than one year and it is recommended that the amount of organic material in the landfill be estimated to calculate the amount of oxygen required. This will aid in scaling the blowers and the estimated time to oxidize the waste volume. The limitation of this technology appears to be the amount of air that the wet, compacted waste will accept. Presuming pore volume and density are correlated, old dense landfill will take much longer to aerate than new freshly filled landfills.

5.2.2 Aeration Operating Temperature Range

The safe operating temperature range for the aerated waste is between 125º F and 170º F. The preferred operating range is between 145º F and 165º F.

5.2.3 Key Monitoring Parameters

There are four key bioreactor operating parameters that are being monitored to assess the progress of aerobic biodegradation in the waste. These are odor, landfill gas composition, pH, and waste temperature. Additional parameters may need to be monitored to satisfy air quality requirements.

Odor

During the composting stage the presence of a sweet smell (probably butyric acid) is pronounced. When this odor disappears, the aerobic stage is over or the waste is too dry and needs to be drenched with water.

Gas Composition

The aerobic phase of gas production is characterized by what is not included in the gas. The gas may include minor amounts of methane and is not as corrosive. The gas does not typically contain significant concentrations of VOCs.

pH

The pH of the leachate is typically acidic due to the type of bacteria degrading the waste. Leachate quality monitoring must make provisions for pH adjustments of leachate. Acidic environments impede methanogenesis bacteria, which are crucial for enhanced biodegradation, and completion of the waste degradation process. The pH must be maintained within the neutral range at all times with the addition of buffering agents.

Waste Temperature

Daily waste temperature measurements can prove beneficial. Spatial measurement is generally a minimum of one per two acres in the mass at the level of aeration. Many technologists also measure gas temperature in recovery pipes or vent temperatures. Within 15 days of aeration in warm weather, the aerated lift should be at 140º F to 145º F unless it is unusually wet or dry. Temperatures at or above 170º F are a cause for concern. It is recommended that material (e.g. water, foam suppression, or CO_2) be used to smother any fire; however water can create gases (vapor) that may cause explosive conditions. It is highly recommended that a fire department or fire suppression expert be consulted for any potential fire condition in a bioreactor. Once the waste temperature reaches ≥ 140º F, a change in temperature of ≥ 20º F in a 48-hour period calls for immediate action. Management should be notified immediately. Most sites doing aeration develop a hot spot procedure as part of a safety drill.

For the purposes of fire monitoring CO can be measured at less than 10ppm, which when elevated to a few hundred ppm could give an early warning that there could be an issue with fire. CO can be measured inexpensively with a Draeger tube in the field. There are other portable measuring devices which can be used to monitor even lower concentrations of CO. Operators may also want to use combination meters (Measurements of O_2 and LEL) to evaluate explosive limits.

5.2.4 System Operations and Maintenance Steps

The following operations and maintenance steps should be followed for optimal system performance:

- Aeration should begin within ten days of completing a new lift of waste. The sooner the better.
- Prior to beginning aeration the working face of the lift to be aerated should be watered. 10 to 25 gallons per bank cubic yard (gal/bcy) is preferred (this includes gallons of biosolids). A minimum of 5 gal/bcy is required. Retrofit wetting is required and varies with each technology chosen.
- The air pressure should be balanced across the header using a pressure gauge once the blower has operated for 24 hours.
- Each aeration pipe should be checked for blockage (watering-out) weekly. Checking the pressure and listening for surges is adequate.

5.3 Management of Moisture Levels

Moisture calculation is a straightforward method for determining the correct amount of moisture to add to the MSW based upon collected data. An optimum moisture level exists for each municipal solid waste landfill that will allow the process of biological stabilization and compaction to proceed at the highest rate possible. Existing literature suggests that the optimum moisture level is between 40-60%.

5.3.1 MSW Moisture Content Determination

The gravimetric procedure for determining the moisture content of MSW is relatively simple and is based in most part upon the methods for determining total solids as presented by *Standard Methods for the Examination of Water and Wastewater* and/or EPA Method 160.3 (see http://www.epa.gov/safewater/methods/). An initial weight is obtained for a 0.5-1.0 kg field sample of MSW. The moist sample is dried at 103-105º C to a constant weight. The percent moisture is calculated as follows:

$$\text{Percent Moisture} = 100 - (\text{dry weight}/\text{wet weight} * 100)$$

For example: A 1000-gram field sample of MSW is obtained and dried. The constant dry weight of the sample is found to be 700 grams. The percent moisture is calculated:

$$\begin{aligned}\text{Percent Moisture} &= 100 - (700/1000 * 100)\\ &= 100 - (0.70 * 100)\\ &= 100 - 70 = 30\%\end{aligned}$$

5.3.2 Moisture Addition Spreadsheet

The moisture addition spreadsheet should be utilized once the percent moisture results are obtained from the laboratory. An explanation of the preparation of the spreadsheet follows.

5.3.2.1 Generation of Spreadsheet Data

A simple algebraic expression was developed to demonstrate the relationship between the total weight for each cubic yard of MSW and any given percent moisture found for collected field samples. A typical moisture level for generic MSW is 25%. The in-place moisture weight, X, was calculated for MSW dry weights from 800 to 2000 pounds/cubic yard from the formula:

$$X = \text{Decimal Fraction Moisture } (\text{Dry Weight Density} + X)$$

For example, on the spreadsheet for Moisture Level of MSW = 25 Percent:
Let the dry weight density equal 1000 pounds/cubic yard and the moisture equal 25% (0.25 as decimal).

$$\begin{aligned}&X = 0.25\,(1000 + X) = 250 + 0.25X\\ &0.75X = 250\\ &X = 333.33 \text{ pounds}\end{aligned}$$

Pounds may be converted to gallons by dividing by 8.34 lbs/gal water.
So, 333.33/8.34 = 39.97gallons.

$$\text{Wet weight} = \text{Dry weight} + \text{Moisture weight} = 1000 + 333.33 = 1333.33 \text{ pounds/yd}^3$$

These equations served to generate the first four columns of the spreadsheet. The equation may be checked by the formula for percent previously presented.

Percent Moisture = 100 - (dry weight/wet weight * 100)
Percent Moisture = 100 - (1000/1333.33 * 100) = 100 - 75 = 25%

5.3.2.2 Addition of Liquids to Achieve Moisture Goal

Using the same spreadsheet line with the MSW moisture level at 25% and 1000 pounds/cubic yard dry weight, the liquid weight present at 35% moisture is calculated.

Calculation check:
$X = 0.35 (1000 + X)$
$X = 350 + 0.35X$
$0.65X = 350$
$X = 538.46$ pounds

Percent Moisture = 100 - (dry weight/wet weight * 100)
= 100 - (1000/1538.46 * 100)
= 35%

The amount of moisture to be added to MSW at 25% to achieve 35% was done by subtraction.

Moisture to be added = 538.46 - 333.33 = 205.13 pounds or 24.60 gallons/cu yd.

The amount of liquid that is required to achieve either 35 or 45% moisture in existing MSW was calculated similarly by determining the moisture weights for 35 and 45% moisture and subtracting the existing moisture weight for the various densities and moisture levels presented.

5.3.2.3 Utilizing the Spreadsheet (Table 5-1)

An example problem will be solved to demonstrate the use of the spreadsheet.
Given:

Landfill volume = 100,000 cubic yards
Moisture = 25%
Dry Weight Density = 1400 lb/cu yd
Desired Percent Moisture = 35%

From spreadsheet:
287.18 lb of liquid need to be added per cubic yard or 34.43 gallons per cubic yard to achieve 35% moisture at 1400 lb/cu yd dry density.

34.43 gallons/cu yd * 100,000 cubic yards MSW = 3,443,000 gallons

Table 5-1. Moisture addition spreadsheet for MSW at 10, 15, 20, 25, 30, 35 and 40 percent moisture

		MOISTURE LEVEL OF MSW = 10 PERCENT						
		Present Moisture			**Liquid to be Added to Achieve:**			
Dry Wt. Density	**Wet Wt. Density**	**10%**	**10%**		**35%**	**35%**	**45%**	**45%**
(lbs/cuyd)	(lbs/cuyd)	(lb/cuyd)	(gal/cuyd)		(lb/cuyd)	(gal/cuyd)	(lb/cuyd)	(gal/cuyd)
800	888.89	88.89	10.66		341.88	40.99	565.66	67.82
900	1000.00	100.00	11.99		384.62	46.12	636.36	76.30
1000	1111.11	111.11	13.32		427.35	51.24	707.07	84.78
1100	1222.22	122.22	14.65		470.09	56.37	777.78	93.26
1200	1333.33	133.33	15.99		512.82	61.49	848.48	101.74
1300	1444.44	144.44	17.32		555.56	66.61	919.19	110.21
1400	1555.56	155.56	18.65		598.29	71.74	989.90	118.69
1500	1666.67	166.67	19.98		641.03	76.86	1060.61	127.17
1600	1777.78	177.78	21.32		683.76	81.99	1131.31	135.65
1700	1888.89	188.89	22.65		726.50	87.11	1202.02	144.13
1800	2000.00	200.00	23.98		769.23	92.23	1272.73	152.61
1900	2111.11	211.11	25.31		811.97	97.36	1343.43	161.08
2000	2222.22	222.22	26.65		854.70	102.48	1414.14	169.56

		MOISTURE LEVEL OF MSW = 15 PERCENT						
		Present Moisture			**Liquid to be Added to Achieve:**			
Dry Wt. Density	**Wet Wt. Density**	**15%**	**15%**		**35%**	**35%**	**45%**	**45%**
(lb/cuyd)	(lbs/cuyd)	(lb/cuyd)	(gal/cuyd)		(lb/cuyd)	(gal/cuyd)	(lb/cuyd)	(gal/cuyd)
800	941.18	141.18	16.93		289.59	34.72	513.37	61.56
900	1058.82	158.82	19.04		325.79	39.06	577.54	69.25
1000	1176.47	176.47	21.16		361.99	43.40	641.71	76.94
1100	1294.12	194.12	23.28		398.19	47.74	705.88	84.64
1200	1411.76	211.76	25.39		434.39	52.09	770.05	92.33
1300	1529.41	229.41	27.51		470.59	56.43	834.22	100.03
1400	1647.06	247.06	29.62		506.79	60.77	898.40	107.72
1500	1764.71	264.71	31.74		542.99	65.11	962.57	115.42
1600	1882.35	282.35	33.86		579.19	69.45	1026.74	123.11
1700	2000.00	300.00	35.97		615.38	73.79	1090.91	130.80
1800	2117.65	317.65	38.09		651.58	78.13	1155.08	138.50
1900	2235.29	335.29	40.20		687.78	82.47	1219.25	146.19
2000	2352.94	352.94	42.32		723.98	86.81	1283.42	153.89

		MOISTURE LEVEL OF MSW = 20 PERCENT						
		Present Moisture			**Liquid to be Added to Achieve:**			
Dry Wt. Density	**Wet Wt. Density**	**20%**	**20%**		**35%**	**35%**	**45%**	**45%**
(lb/cuyd)	(lbs/cuyd)	(lb/cuyd)	(gal/cuyd)		(lb/cuyd)	(gal/cuyd)	(lb/cuyd)	(gal/cuyd)
800	1000.00	200.00	23.98		230.77	27.67	454.55	54.50
900	1125.00	225.00	26.98		259.62	31.13	511.36	61.31
1000	1250.00	250.00	29.98		288.46	34.59	568.18	68.13
1100	1375.00	275.00	32.97		317.31	38.05	625.00	74.94
1200	1500.00	300.00	35.97		346.15	41.51	681.82	81.75
1300	1625.00	325.00	38.97		375.00	44.96	738.64	88.57
1400	1750.00	350.00	41.97		403.85	48.42	795.45	95.38
1500	1875.00	375.00	44.96		432.69	51.88	852.27	102.19
1600	2000.00	400.00	47.96		461.54	55.34	909.09	109.00
1700	2125.00	425.00	50.96		490.38	58.80	965.91	115.82
1800	2250.00	450.00	53.96		519.23	62.26	1022.73	122.63
1900	2375.00	475.00	56.95		548.08	65.72	1079.55	129.44
2000	2500.00	500.00	59.95		576.92	69.18	1136.36	136.25

		MOISTURE LEVEL OF MSW = 25 PERCENT						
		Present Moisture			**Liquid to be Added to Achieve:**			
Dry Wt. Density	**Wet Wt. Density**	**25%**	**25%**		**35%**	**35%**	**45%**	**45%**
(lb/cuyd)	(lbs/cuyd)	(lb/cuyd)	(gal/cuyd)		(lb/cuyd)	(gal/cuyd)	(lb/cuyd)	(gal/cuyd)
800	1066.67	266.67	31.97		164.10	19.68	387.88	46.51
900	1200.00	300.00	35.97		184.62	22.14	436.36	52.32
1000	1333.33	333.33	39.97		205.13	24.60	484.85	58.14
1100	1466.67	366.67	43.96		225.64	27.06	533.33	63.95
1200	1600.00	400.00	47.96		246.15	29.51	581.82	69.76
1300	1733.33	433.33	51.96		266.67	31.97	630.30	75.58
1400	1866.67	466.67	55.96		287.18	34.43	678.79	81.39
1500	2000.00	500.00	59.95		307.69	36.89	727.27	87.20
1600	2133.33	533.33	63.95		328.21	39.35	775.76	93.02
1700	2266.67	566.67	67.95		348.72	41.81	824.24	98.83
1800	2400.00	600.00	71.94		369.23	44.27	872.73	104.64
1900	2533.33	633.33	75.94		389.74	46.73	921.21	110.46
2000	2666.67	666.67	79.94		410.26	49.19	969.70	116.27

		MOISTURE LEVEL OF MSW = 30 PERCENT						
		Present Moisture			Liquid to be Added to Achieve:			
Dry Wt. Density	**Wet Wt. Density**	**30%**	**30%**		**35%**	**35%**	**45%**	**45%**
(lb/cuyd)	(lbs/cuyd)	(lb/cuyd)	(gal/cuyd)		(lb/cuyd)	(gal/cuyd)	(lb/cuyd)	(gal/cuyd)
800	1142.86	342.86	41.11		87.91	10.54	311.69	37.37
900	1285.71	385.71	46.25		98.90	11.86	350.65	42.04
1000	1428.57	428.57	51.39		109.89	13.18	389.61	46.72
1100	1571.43	471.43	56.53		120.88	14.49	428.57	51.39
1200	1714.29	514.29	61.66		131.87	15.81	467.53	56.06
1300	1857.14	557.14	66.80		142.86	17.13	506.49	60.73
1400	2000.00	600.00	71.94		153.85	18.45	545.45	65.40
1500	2142.86	642.86	77.08		164.84	19.76	584.42	70.07
1600	2285.71	685.71	82.22		175.82	21.08	623.38	74.75
1700	2428.57	728.57	87.36		186.81	22.40	662.34	79.42
1800	2571.43	771.43	92.50		197.80	23.72	701.30	84.09
1900	2714.29	814.29	97.64		208.79	25.03	740.26	88.76
2000	2857.14	857.14	102.77		219.78	26.35	779.22	93.43

		MOISTURE LEVEL OF MSW = 35 PERCENT						
		Present Moisture			Liquid to be Added to Achieve:			
Dry Wt. Density	**Wet Wt. Density**	**35%**	**35%**		**35%**	**35%**	**45%**	**45%**
(lb/cuyd)	(lbs/cuyd)	(lb/cuyd)	(gal/cuyd)		(lb/cuyd)	(gal/cuyd)	(lb/cuyd)	(gal/cuyd)
800	1230.77	430.77	51.65		0.00	0.00	223.78	26.83
900	1384.62	484.62	58.11		0.00	0.00	251.75	30.19
1000	1538.46	538.46	64.56		0.00	0.00	279.72	33.54
1100	1692.31	592.31	71.02		0.00	0.00	307.69	36.89
1200	1846.15	646.15	77.48		0.00	0.00	335.66	40.25
1300	2000.00	700.00	83.93		0.00	0.00	363.64	43.60
1400	2153.85	753.85	90.39		0.00	0.00	391.61	46.96
1500	2307.69	807.69	96.85		0.00	0.00	419.58	50.31
1600	2461.54	861.54	103.30		0.00	0.00	447.55	53.66
1700	2615.38	915.38	109.76		0.00	0.00	475.52	57.02
1800	2769.23	969.23	116.21		0.00	0.00	503.50	60.37
1900	2923.08	1023.08	122.67		0.00	0.00	531.47	63.73
2000	3076.92	1076.92	129.13		0.00	0.00	559.44	67.08

		MOISTURE LEVEL OF MSW = 40 PERCENT						
		Present Moisture			**Liquid to be Added to Achieve:**			
Dry Wt. Density	**Wet Wt. Density**	**40%**	**40%**		**35%**	**35%**	**45%**	**45%**
(lb/cuyd)	(lbs/cuyd)	(lb/cuyd)	(gal/cuyd)		(lb/cuyd)	(gal/cuyd)	(lb/cuyd)	(gal/cuyd)
800	1333.33	533.33	63.95		0.00	0.00	121.21	14.53
900	1500.00	600.00	71.94		0.00	0.00	136.36	16.35
1000	1666.67	666.67	79.94		0.00	0.00	151.52	18.17
1100	1833.33	733.33	87.93		0.00	0.00	166.67	19.98
1200	2000.00	800.00	95.92		0.00	0.00	181.82	21.80
1300	2166.67	866.67	103.92		0.00	0.00	196.97	23.62
1400	2333.33	933.33	111.91		0.00	0.00	212.12	25.43
1500	2500.00	1000.00	119.90		0.00	0.00	227.27	27.25
1600	2666.67	1066.67	127.90		0.00	0.00	242.42	29.07
1700	2833.33	1133.33	135.89		0.00	0.00	257.58	30.88
1800	3000.00	1200.00	143.88		0.00	0.00	272.73	32.70
1900	3166.67	1266.67	151.88		0.00	0.00	287.88	34.52
2000	3333.33	1333.33	159.87		0.00	0.00	303.03	36.33

5.4 Instrumentation

Table 5-2 describes useful instrumentation for essential monitoring parameters of bioreactor landfills.

Table 5-2. Landfill instrumentation for bioreactor projects

Parameter	**Instrumentation**	**Typical Spacing or number per acre**
Temperature (to measure waste mass or leachate temperature)	4” stainless steel thermistor Series T 15000 Item QT06005-096Z 10000 Ohm CS Probe	As determined by budget and bioreactor design team requirements
Pressure Transducers (to measure liquid head on liner system)	PTX 1830 Range 0-1 psi 9-30 vDC 4-20 mA output cable included	As determined by budget and bioreactor team requirements
Moisture (for measuring in-situ moisture content)	Use perforated pipe filled with gravel with two stainless steel screws and measure resistance across the probe.	As determined by budget permit requirements
ORP (redox Potential) This device is a research tool; life in landfill environment is questionable.	Cole-Parmer ORP electrode or equivalent w/LED readout controller	As determined by budget and bioreactor team requirements
Landfill Stability	Inclinometers, piezometers, load cells, settlement markers	As determined by budget and bioreactor team requirements

5.5 Liquids Recirculation and Addition

As earlier sections described various methods of adding liquid to a bioreactor, this section focuses on the operational considerations of adding liquid to the bioreactor. The methods of recirculation that have been used to date include surface infiltration ponds, surface spraying, horizontal trenches, vertical wells, vertical injection needles, vertical injection wells, drip irrigation tubing and area infiltration systems. All have particular applications and limitations.

5.5.1 Surface and Surface Infiltration Ponds

Some operators have constructed shallow infiltration pond(s) on the surface of a solid waste landfill. Leachate is pumped into the pond and allowed to infiltrate. There are numerous limitations to this method of recirculation, including odor concerns, aesthetics, safety, rainwater infiltration, cold weather operation, etc. Infiltration ponds are generally not an acceptable method of liquids recirculation for modern landfills. They can be used if small, (<400 ft^2) otherwise they tend to smell and attract birds. A recent modification of this technique using compost rejects or wood chips as a filtration media in small ponds or galleries has allowed operators to infiltrate solids containing materials and filter out the solids as the liquids move into the landfill.

5.5.2 Spray Systems

Leachate can be sprayed using a tanker truck, water wagon, portable tank, plus fire hose or irrigation type sprinkler. Tanker trucks or water wagons that are typically available at a landfill site for dust control and similar water needs are often used to transport leachate to the working face where it is sprayed on the open trash face. This pre-wetting of the open face tends to improve compaction and is a recommended component of all recirculation programs. Some operators have also considered installing a leachate tank on the compactor allowing the leachate to be distributed as the compactor works. If the tanker truck or water wagon is used for both dust control and leachate hauling, a decontamination plan should be developed. A typical decontamination plan usually involves a rinse with clean water after completion of leachate hauling and the discharge of the rinse water to the working face or sewer. Spraying liquids on the working face should be done away from the area where trash trucks are unloading. The spray could be done at the top of the working face slope if trash trucks are unloading at the bottom of the working face. Spraying must be avoided when wind conditions tend to cause misting toward the working face staff. Spraying may also be discontinued if wind conditions are unfavorable with respect to carrying odors off site toward neighbors.

Sprinkler systems distribute the liquid to a relatively large, but controlled area with minimal equipment and labor requirements. Sprinklers should be periodically moved to avoid overdosing a particular area. The misting common with sprinkler delivery can sometimes lead to concerns over odor or air emissions and evaporation. Evaporation reduces the total volume of leachate and is not necessarily a benefit since the goal of a recirculation system is to return liquid to the waste mass and raise the overall moisture content.

5.5.3 Horizontal Trenches

Horizontal recirculation trenches are typically the easiest to construct, cheapest, and most effective recirculation system available for the majority of landfills. Trenches placed in the waste fill at regular horizontal and/or vertical intervals and backfilled with permeable material (aggregate, fluff, loose waste, shredded tires, wood chips, crushed glass, etc.) provide a method for uniformly distributing leachate. While sand is not a recommended permeable material, due to its propensity to clog, tire chips work well in shallow burial applications, but with depth, appear to compress with the overburden resulting in reduced flow capacity. Perforated piping is generally included in the trench. Trench systems can be fed by gravity or pressure although pressure systems seem to operate better because they typically allow better flow distribution throughout the length of the pipe and benefit from full pipe flow and the cleansing action associated with it. A typical vertical interval for horizontal trenches is 30-50 feet, however, the zone of influence of a horizontal trench is a much-debated question. Deeper rather than shallow trenches seem to allow more flexibility for liquids recirculation. Trenches are generally dug using a backhoe where the trench width and depth is usually governed by the backhoe bucket width and the maximum reach of the boom. Trenches should be dosed periodically and then allowed to 'rest' before re-dosing. The optimum period for dosing and resting must be determined based on trial and error.

5.5.4 Vertical Injection Needles

Perforated steel pipe, typically two inches in diameter with a tapered end, can be driven into a waste mass using a backhoe. The benefits include low cost, no drilling, and fast installation. The primary disadvantage is that the needles can accept a limited quantity of liquid. Vertical needles are generally sacrificial and are abandoned in place when they no longer accept reasonable volumes of liquid.

5.5.5 Area Infiltration Systems

Some sites have installed layers, typically one to two feet thick, of highly permeable materials in an attempt to provide uniform distribution of recirculated leachate over the widest possible area. This could be aggregate, tire chips, wood chips or any other permeable and available material. Perforated distribution pipes placed in the permeable zone, vertical wells, gravel columns, or some combination of these components, are used to introduce liquid into the permeable zone. The cost of the permeable material tends to be quite high unless waste streams (e.g. tire chips) can be used for this layer. Innovative operations have stockpiled C & D for this use historically.

5.5.6 Combined Gas Extraction/Recirculation

It may be possible to combine the piping system used for landfill gas collection with a liquids recirculation system. This will require very careful and thoughtful design, construction, and monitoring procedures to avoid liquids in gas wells that interfere with LFG collection.

5.5.7 Application Frequency

Liquids addition may not be a continuous process. It will be desirable to temporarily stop recirculation and addition as the moisture level in a certain zone increases. Various recirculation zones can be dosed at intervals determined by field and climate conditions. Experience with liquids recirculation systems, examples of which are identified in Table 5-3, and discussions with state solid waste regulators have shown the following real or perceived potential concerns. These concerns should be addressed during the design phase of the project:

- Non-uniform moisture distribution
- Poor flow distribution due to daily cover layers

- Formation of scale and other depositional blockages
- Potential clogging of leachate collection system components
- Failure of piping components due to waste settlement or overburden pressure
- Buildup of hydraulic head on liner system, which may be caused by pump system failure, or other complicating factors such as leachate system clogging.
- Leachate seep mitigation and repair plan
- Increased landfill gas production
- In addition to leachate addition, the RD&D rule allows for liquids and sludge's that do not pass the paint filter test. It is critical that outside liquids be screened and profiled.

Table 5-3. Examples of full scale liquids recirculation hydraulic application rates

Recirculation Method	Application Rates
Vertical Injection Wells	60-150 Gal/Hour per 2.5" diameter well, non-continuous flow 1200-12,100 Gal/Hour per 48" diameter well non-continuous flow
Horizontal Trenches	25-50 Gal/foot of trench length per day at 60-100 gpm
Spray Irrigation	18 gal/square foot of landfill area 0.02-0.08 gal/square foot of landfill area

5.6 Operational Issues

In order to optimize the effectiveness of a liquids recirculation program, it may be desirable to implement certain operational practices that differ from current procedures. At least one operator has found that dosing the landfill rather than continuous application was more beneficial. Dosing was accomplished by intermittently injecting liquids into the landfill trenches. This is done by letting the liquids seep into the landfill and then applying additional liquids to the trenches on a periodic basis.

5.6.1 Daily/Intermediate Cover

Recirculated liquid must be free to move within the landfill. Thick, low permeability layers of daily cover will impede the effectiveness of moisture distribution in the landfill and will increase the likelihood of sideslope outbreaks. Highly compacted soil daily cover creates barriers within the landfill. Options for daily cover that are more compatible with recirculation include tarps, plastic sheeting, and foam. It is also possible to use a highly permeable cover such as sand or to strip the daily cover off at the beginning of each new working day. It must be noted that the use of these alternate daily covers may require a permit modification and notification to the regulatory authority.

Daily cover slopes are often graded flat or sloped to drain water toward the outer slopes of the landfill. For recirculation and bioreactor sites, it may be helpful to slope the daily cover (or top of trash) surface back in towards the landfill. This will help direct recirculated liquids back into the waste mass and help prevent sideslope outbreak seepage. Of course, alternate daily cover should also be used, or for sites that use soil for daily cover, the daily cover should be removed before each day's filling.

Some landfills use revenue generating cover as a traction enhancing material. As an example, the Middle Peninsula Landfill in Virginia receives a large amount of green waste, such as stumps, branches, etc. When they have collected a sufficient quantity, an outside contractor is hired to bring in a tub grinder and grind the wood waste into chips. This chip material is spread, usually to a thickness of three to four inches, on landfill working areas and temporary roads as a traction enhancing material. The wood waste also absorbs moisture and helps to control dust. This is a much better option than watering. Since watering often turns unpaved roads from dust to mud, the wood chips hold moisture for a longer time without drying and help to suppress moisture loss. Depending on the permit, this type of material is also suitable as an alternate daily cover.

The Countryside Landfill has been designed and operated to facilitate liquids recirculation and moisture addition. The landfill is permitted and allows liquids recirculation and uses construction and demolition waste for alternate daily cover. This creates a permeable media that avoids the isolation of leachate into discrete cells and allows good lateral and vertical distribution of leachate and moisture. The (vertical and horizontal) hydraulic conductivity of the MSW is estimated at 10^{-3} cm/sec and the C&D is approximately 10^{+1}cm/sec. This encourages lateral and vertical distribution of leachate. The operator should be aware that use of C&D screenings with high wallboard content (see section 1.5 of this document) could result in excessive gaseous hydrogen sulfide emissions, which may require installing a scrubber in the gas collection system. The operation also uses clayey soil daily cover when MSW is 100’ near outward side slopes to prevent leachate seeps. More information about this landfill is available at http://yosemite.epa.gov/r5/il_permt.nsf.

5.6.2 Working Face

The working face should be pre-wetted using a tanker truck, water wagon or spray system (See section 5.5 for precautions). Pre-wetting the waste at the working face has the advantages of increasing the moisture content of the waste, improving compaction and reducing windblown litter. In most cases, pre-wetting should be suspended on rainy days to avoid excess liquid.

5.6.3 Landfill Gas Issues

Early landfill gas production with bioreactor operation can be viewed either as an advantage or as a disadvantage depending on how the particular bioreactor is operated (e.g., how much gas is generated, the generation rate, collection system effectiveness, and gas chemistry), how the bioreactor is regulated (e.g., air emissions and groundwater protection issues), and a variety of public and health concerns (e.g., odor, explosion potential, and positive/negative opinions regarding alternatives for LFG management and use).

Anaerobic bioreactors generate LFG (principally methane and carbon dioxide) earlier in the process and at a much higher rate than the traditional landfill. Bioreactor LFG is generated over a shorter period of time because the LFG emissions begin early and decline as the accelerated decomposition process depletes the source waste. Benefits offered by this aspect of the bioreactor process are the availability of gas for productive uses and the potential for LFG impacts (to the atmosphere, groundwater, or to potential receptors) are reduced.

The ITRC Alternative Landfill Technologies Team strongly recommends that all landfill projects, and especially bioreactors, develop a project-specific plan for LFG management strategies at an early stage in the project. This recommendation relates to the potential significance of LFG generation and to the necessity to integrate design development and construction with a variety of applicable regulatory environmental protection requirements and technical issues.

LFG-related environmental protection requirements of Federal and State regulations

- Health protections requirements. RCRA Subtitle D (40 CFR 258) regulations (and corollary State regulations) include monitoring and response requirements to provide assurance that LFG migration to off-site areas does not exceed specific criteria (i.e., 40 CFR 258.23 prohibits off-site migration of gas at concentrations above the explosive limit).
- Atmospheric emissions prevention. Numerous Federal and State regulations mandate prevention of unacceptable atmospheric releases. Measures to prevent such releases are required when potential or actual releases reach unacceptable levels.
- Groundwater protection requirements. Numerous Federal and State regulations mandate prevention of unacceptable groundwater impacts. Subsurface migration of LFG away from a landfill can cause impacts to groundwater. For example, in arid California, practical experience of ITRC ALT Team members indicates that as much as 80% of groundwater impacts resulting from the presence of a landfill are caused by landfill gas and not by leachate release. Conversely, in humid South Carolina, ITRC ALT Team member experience is that LFG is seldom the sole cause of observed groundwater impacts.

LFG-related technical issues

Practical experience of landfill operators (and their technical resource groups) shows that final cover type can affect future environmental conditions in positive and negative ways, requiring a site-specific determination of the appropriate technology.

- Conventional (low permeability) covers can facilitate incorporation of gas collection measures and allow gas capture for beneficial use as well as attainment of local air quality requirements, but also can proliferate increased gas pressures and possible subsurface movement of gas in areas that could be susceptible to migration (e.g., liner tie-ins). The migration of landfill gas could result in groundwater quality being affected in nearby groundwater monitoring wells.
- Alternate final covers (AFCs) are intended to control, but not prevent moisture infiltration and, as a result, are potentially more permeable to gas infiltration than low permeability covers. AFCs may provide better groundwater protection against LFG-related impacts, but if gas recovery systems are not designed, constructed, and properly implemented, they may allow more gas emissions to the atmosphere. Still, AFC-covered bioreactors can be designed to allow sufficient natural infiltration to support bioreactor processes while providing mechanisms to prevent unacceptable atmospheric releases. This can be done either by incorporating gas collection systems (albeit, less effective than those used with conventional covers) or by enhancing natural methane degradation processes (i.e., oxidation).

Some additional technical issues significant to the use of bioreactor technology and LFG generation are noted below.

- Collected gas either must be destroyed (such as by flaring) or put to productive use. Such uses might include on-site uses, such electric power generation. Each approach requires a significant pre-design and pre-construction effort or to find gas or power customers.
- Alternative gas management should be considered where the long-term viability of a gas use method is uncertain. Also, gas generation might continue after landfill closure, but the manner of gas use prior to closure might no longer be available. An active system used during the high gas generation period of the landfill might be changed to a passive system after closure.

5.6.4 Final Cover

The timing for application of final cover will have to be considered in light of operational and permit requirements. To take advantage of the airspace increase created by liquids recirculation, the cell should stay open without a final cap as long as possible. This may have some negative implications in terms of gas control and leachate generation rates. There are various alternatives for interim caps, such as a thin membrane rain cap held down with tires, sandbags or other weighting devices. It must be assured that interim cap alternatives are evaluated in light of any existing regulations or guidance. A more stable and settled the waste mass should reduce long-term maintenance of the final cap system. To maximize the usefulness of any enhanced airspace, the space should be usable within the first two to three years of commencing the recirculation.

Alternative final caps (See ITRC ALT-2 2003) are also becoming more widely investigated and accepted. Some of the more promising include:

- *Biological Permeable Cap*: This cap, with a 1 meter ± zone of compost, acts as a methane oxidation layer.
- *Capillary Barrier Cap System*: This cap design has typical layers including (top to bottom): vegetation, topsoil, fine-grained soil ($1x10^{-6}$ cm/sec-saturated), capillary barrier layer (coarse-grained layer, $1x10^{-2}$ cm/sec-saturated), intermediate cover or final grading layer over waste. The theory of operation is that infiltration water enters the fine-grained layer and water is removed from layer by evapotranspiration. During dormancy of the cover vegetation, the water accumulates and migrates to the bottom of the layer. The coarse-grained layer acts as a hydraulic barrier to movement.
- An *Evapotranspiration Cap System:* This option uses thicker soil caps with trees or vegetation. The soil layer acts as a sponge storing infiltrated water. The stored water is evaporated or transpired via the vegetation before it can migrate downward into the waste mass. Design considerations include climate (solar radiation, cloud cover, precipitation, temperature, humidity, etc), soils, and vegetation.

Advantages of alternative final covers are described in more detail in ITRC ALT-2, 2003 and USEPA, 2004.

5.6.5 Odor

An aggressive odor control plan should be developed for virtually all landfills, but it is essential for sites that intend to recirculate or utilize bioreactor practices. An odor problem could cause a negative reaction among nearby property owners and regulators, whether or not due to recirculation/bioreactor operations. Some operators have experienced increased odor problems that seem to be related to the recirculation of leachate. This is likely aggravated by the structures (e.g. vertical manholes), which provide access to the fill for the reintroduction of leachate and the higher rates of LFG generation, which may not be adequately collected by the sites' collection system.

The first step in an odor control plan is to evaluate the need for additional LFG collection capability to handle the higher flow rates associated with 'wet' MSW. Leachate sumps, riser pipes, cleanout pipes and similar access structures should be connected to the gas system to avoid fugitive emissions. Some landfill practices, e.g. accepting biosolids in wet form as a moisture source can also aggravate odor problems if not properly managed. Note that odor control may be necessary even after the gas system is operational.

Types of material that may contribute to odor include:

- Waste (including sludges and biosolids)
- Petrucible waste
- Septics
- Makeup water (wastewater from outside sources)
- Leachate
- LFG condensate
- Sulfate

There are several methods to place the waste to minimize odors:

- Biosolids may cause odor at the working face
- Placement of petrucibles above waste that can act as an absorbent
- Minimization of working face
- Maintainenance of daily cover
- Placement according to prevailing wind
- Blending to neutralize odor
- Masking agents
- Barometric temporal considerations
- Injection
- Covered infiltration gallery

5.6.6 Public Relations-Internal

Landfill equipment operators and truck drivers who are in the area of working face pre-wetting operation may be concerned and should be protected from unreasonable exposure to odors and fugitive emissions. Landfill staff should attend training specific to the recirculation option in use.

5.6.7 Compaction

The efficient compaction used at conventional landfills might be self-defeating from the standpoint of moisture distribution within a bioreactor landfill. The highly compacted (tight) layers of trash reduce the ability of moisture to evenly saturate the mass and may cause problems with leachate outbreaks. To optimize recirculation effectiveness, it may be more efficient to do an initial loose compaction and then follow at some later time with more rigorous compaction (top 40-50 feet) after moisture has been well distributed. Another option is to aerobically compost waste with the controlled addition of air and moisture then landfill this reduced volume of semi-stabilized waste.

5.6.8 Leachate Pre-Treatment Issues

Some researchers in the field of bioreactors recommend certain amendments to or pre-treatment of leachate that is to be recirculated. The most common recommendations include:

- *Nutrient augmentation:* MSW leachate is sometimes deficient in nutrients. However, the addition of chemical nutrients such as phosphate and nitrate does not seem to provide any further enhancement since a nutrient deficit is generally not a limiting factor in a landfill anaerobic degradation.
- *Heating:* Some suggest that raising the temperature of the leachate prior to reintroduction into the landfill would be beneficial. The theory is that since biological activity is more efficient at higher temperatures, heating leachate will help to “kick-start” the biological processes. Recent team experience in Canada suggests that large volumes of leachate under 50°F should be avoided in large quantities because of the potential of cooling the entire mass.
- *Treatment:* Some researchers feel that a pH adjustment and filtration system should be installed to partially treat and adjust the pH of leachate, especially after multiple passes through the waste mass.

Most researchers seem to be confident that none of these treatments are necessary for a successful recirculation project.

5.6.9 Winter Operation

Liquids recirculation can be continued in winter months, particularly in buried pipe distribution systems. It may be necessary to provide freeze protection to aboveground components of the system. It is also a good operational practice to lay freeze-prone pipes at a slope and provide a drain at the low point. Pre-wetting of the working face and other applications that involve manual contact with the liquid may not be appropriate on cold days. Many operators are considering seasonal aeration to utilize the excess heat generated by short-term aerobic degradation. In northern climates where snow is used for cover, seasonal aeration will melt the garbage-insulated snow in the cell and increase degradation.

According to Tolaymat in EPA 2004 Reports page 8 Section 4.2.1.1:

> “Research suggests that anaerobic processes occur best within either mesophilic (30-38°C) or thermophilic (50 to 60°C) temperature ranges (McCarty 1964; Parkin and Owen

> 1986). Optimum methane generation from solid wastes, however, occurred at 41°C (Harts et al. 1982). Regardless of the operational temperatures, the maintenance of a uniform temperature is considered to be fundamental to anaerobic stabilization process efficiencies. Historically, conventional landfills leachate temperature ranged from 7 to 25°C while bioreactor landfills leachate ranged from 6 to 37°C (EPA 2003)."

It is likely not cost effective to design a process to maintain a constant and optimal operating temperature for an anaerobic bioreactor.

5.6.10 Retrofit Liquid Application Rates

Site-specific guidelines must be developed as operating experience is gained at the landfill. For as-built bioreactors, the dosage per day is dependant on the sorptive capacity of the trash and the amount of rain. For retrofit bioreactors, Table 5-4 should be considered as a starting point only. This information is based on a limited number of data points and is in continual refinement.

Table 5-4. Retrofit liquid dosing per day based on footprint of cell and no rain or snow

Cell Density (lbs./cubic yard)	**Liquid addition based on cell foot print in acres (g/dy)**
2000	500
1800	1000
1600	2000
1400	2400
1200	2600-3000

5.7 Performance Monitoring

The actual monitoring system required to demonstrate the effectiveness and the subsequent optimization of a bioreactor is unique to the site conditions and the regulatory, political, and stakeholder interests and concerns in the project. However, even a more exhaustive monitoring program should have room for flexibility given a demonstrated predictability to the monitoring results. A focus of the sampling and analysis program for bioreactor demonstrations is to understand carbon and nitrogen cycling in solids, liquids, and gases of the landfill system. Accordingly, extensive sampling of waste, leachate, landfill gas, and surface emissions is being performed. Some of the monitoring discussed in the following sections will result in collecting more information than may be necessary for the optimization of a bioreactor. Some of the information could be used to advance the general science and art of designing, constructing, and operating bioreactors.

Several unique techniques for waste sampling are used. Bucket auguring are used to obtain specific weights of known volumes of solid waste and are used to calculate densities of waste mass in field investigations. Global positioning systems (GPS) are used to estimate waste mass density as opposed to manual surveying or settlement plates. Available nitrogen and phosphorus measurements in the waste are worth further collection and evaluation to track nitrogen mass balance and to determine if phosphorus is rate limiting to biological stabilization.

Achieving waste stabilization is the ultimate goal of landfill bioreactor operations. However, characterizing and controlling the spatial and temporal progress of stabilization at an operating bioreactor landfill still poses significant challenges. The heterogeneous nature of waste and the complex interaction of the physical, chemical, and biological processes occurring in the solid, liquid, and gas phases require a comprehensive and multimedia approach to monitoring at bioreactor landfill sites. This section presents a recommended sampling and analysis strategy; however, to fully evaluate and optimize bioreactor operations the parameters, frequency and distribution is dependent on the site, waste, construction, and operation. Monitoring the program must be tailored to effectively and efficiently evaluate the operation and stability of the bioreactor landfill operation.

5.7.1 Baseline Data Collection (Retrofit Landfills)

Establishing baseline (existing) conditions at a retrofit bioreactor project will allow future determination of the effectiveness of the program. Baseline conditions can be established via a drilling program. For instance, waste samples are taken from a borehole and analyzed for temperature, moisture content, in-place density, and other parameters as necessary. Municipal solid waste sampling procedures are the same as those normally used in the industry for gas well installation. Boreholes are advanced using a 3' bucket auger. Cover material is discarded, and samples are collected in vertical sections of known height. These samples are not chilled, frozen, or iced.

Temperature of the waste is taken at a minimum of every five feet by placing a long-stemmed, metal, glass-faced thermometer into the waste just as it is retrieved. An elevated temperature in the MSW is considered an indicator of good microbial activity.

Table 5-5, 5-6, and 5-7 have been modified from Tolaymat, 2004 by the team. The parameters and the frequency of monitoring reflect experience from team members who have designed, and regulated bioreactor landfills. As any bioreactor landfill project progresses the sampling plan will be modified as appropriate. Standard Method references are listed in Table 5-8.

Table 5-5. Parameter and collection frequency for landfill studies

LEACHATE		SOLID WASTE		GAS	
Parameter	**Interval**	**Parameter**	**Interval**	**Parameter**	**Interval**
Head on liner	Short and long term	Waste Temperature	18 months. Utilize gas temp coupled with direct waste reading for optimization but not to be continued indefinitely on a daily basis. Recommended but not mandatory except in an aerobic reactor to recognize temperature spikes to suppress fires	landfill gas flow/production	weekly to monthly

LEACHATE		SOLID WASTE		GAS	
Parameter	**Interval**	**Parameter**	**Interval**	**Parameter**	**Interval**
Temperature	Monthly in the short term. It is not a recommended monitoring parameter for the long term except to recognize methanogenic activity.	Waste Settlement (GPS)	Annually	$CH_{4,}$	Weekly – Quarterly depending on stability of the flow
Leachate production	Daily until injected water collects in the sumps, then only to maintain the head on liner.	Average Volatile Solids (This could be replaced with	18 months	CO_2	Weekly – Quarterly depending on stability of the flow
COD-Chemical Oxygen Demand	Monthly - quarterly			O_2	Weekly – Quarterly depending on stability of the flow
BOD-Biochemical Oxygen Demand	Monthly - quarterly	Moisture content (wet based)	18 months.	HAPs (Hazardous Air Pollutants)	NESHAPS requires monitoring begin within 180 days
Ammonia-Nitrogen	(NH_3-N) monthly in the short term and at intervals that will identify high concentrations that may impact the methanogens	Density	Annually (As it affects liquid recirculation)	NMOC (non-methane organic carbon)	See HAPs
Nitrate-Nitrogen	(NO_3-N) Monthly in the short term and may be reduced for aerobic only. No monitoring for anaerobic.	pH	18 months (indicator of degradation)	surface emission monitoring	See HAPs
Nitrite-Nitrogen	(NO_2-N) Monthly in the short term and may be reduced for aerobic only. No monitoring for anaerobic.	Cellulose, Hemicellulose & Lignin	18 months (can be substituted by Volatile solids)		
pH	Monthly in the short term and then move to quarterly to semi-annually in the long term.	Average Volatile Solid –	18 months	Carbon Dioxide	weekly

LEACHATE		SOLID WASTE		GAS	
Parameter	**Interval**	**Parameter**	**Interval**	**Parameter**	**Interval**
VOC	Quarterly			Oxygen – Weekly	
SVOC	Quarterly			Carbon Monoxide	Weekly
TOC-Total Organic Carbon	Monthly				
Total dissolved solids	Monthly				
sulfate, chloride,	Monthly				
Volatile Organic Acids	Quarterly				
Conductance	Monthly				
Alkalinity	Monthly				
RCRA hazardous metals Appendix I	Quarterly				

Table 5-6. Mass loading calculation parameters

Visual Landfill Inspection	Daily
Geotechnical Landfill Stability	As necessary
Mass of Landfilled MSW	Daily
Mass of Landfilled Construction and Demolition Waste	Daily
Mass of Soil (other than daily cover)	Daily
Type of Daily Cover	Daily
Mass of Daily Cover	Daily
Landfill volume	Quarterly

Table 5-7. Liquid additions monitoring

Parameter	Frequency	Units
Volume of leachate and landfill gas condensate added	Daily	L (gal)
Precipitation (Rainfall and snowfall)	Daily	mm (inch)
Volume Outside Liquid Added (e.g., Groundwater, Non-Hazardous Industrial Waste Water, etc)	Daily	L (gal)
Volume of Leachate Generated/extracted	Daily	L (gal) of leachate generated by the bioreactor cells only
Mass of Sludge Added	Daily	Mass (tons)
Wet Basis Moisture content of sludge added	Daily	Percent (M/M)

Recommended methods of analysis for the parameters above can be found in Tolaymat, 2004.

5.7.2 Leachate Parameters

The bioreactors must be compliant with the subtitle D rating of the liners. This rule requires no more than 30 cm of head on the liner. Present bioreactor designs seem to be effective in maintaining the head on the liner requirements. Confusion exists due to a lack of understanding the permeability resulting from the different layers of landfill construction and the sorptive capacity of the trash. Solid waste composed of paper, cardboard, food waste, and building debris has the capacity to retain gallons of water per cubic yard. As the waste degrades, water is lost through several mechanisms. It is consumed during the anaerobic decomposition (reaction) and is lost to the gas recovery system as vapor and through evaporation prior to capping. Even so, slight increases in leachate production may be observed over time as the holding capacity of the waste is lowered due to stabilization and densification.

Monitoring BOD, COD, and forms of nitrogen trends appears to be the most practical method of measurement for relating leachate quality to solid waste stabilization. The nitrogen components (TKN, ammonia, nitrite, and nitrate) give an overall measurement of the biological changes taking place in the MSW. Ammonia climbs significantly over time in a bioreactor and liquids recirculation systems as anaerobic degradation releases ammonia previously bound as organic nitrogen. The establishment of a mathematical model for determining the relationship between the measured leachate parameters and the degree of MSW stabilization is critical.

The pH in bioreactor leachate has been observed to increase towards pH 8 during the anaerobic phase. Routine monitoring the pH trend will establish whether the bioreactor is encountering a recurrence of acid conditions and possibly solubilizing compounds in the landfill.

Volatile and semi-volatile organics should decrease with the increasing biological activity as the waste become degraded. This will be determined during operator demonstrations and monitored routinely.

Dissolved solids and inorganics are important to measure in order to determine the potential for precipitation in highly active systems. Total dissolved solids TDS as well as some inorganics (like calcium and iron) can give an indication if potential clogging concerns for leachate collection systems. High TDS levels mean that some of these solids may deposit on the leachate collection lines. Other parameters can be used to evaluate clogging potential; however, TDS is the least expensive.

Total phosphorus and ortho-P may be limiting to biological reactions at any time in certain landfills and some residual should be present in the leachate to ensure this does not occur.

5.7.3 Municipal Solid Waste Parameters

The measurement of changes in the waste mass data will suggest whether the bioreactor is performing efficiently. Samples are difficult and expensive to collect since they require drilling into the waste mass. Additionally solid waste is not heterogeneous and a fairly large number of samples are needed from each borehole to draw valid conclusions. Researchers are using bucket auger rigs that are 76.2 cm to 91.44 cm (30" and 36") in diameter. The USEPA/WM CRADA C (see Section 1.4 of this report) is collecting samples in 3-meter intervals and Sample size is extremely important to decrease variability. Typical samples are 20 kg and can be as large as 225 kg. It is suggested that settlement and leachate quality become the key measures of the biodegradation and that MSW parameters become qualitative proof.

5.7.3.1 Waste Temperature

Waste temperature is measured using thermocouples as often as every 20 feet bgs to within 10-15 feet of the liner in retrofit bioreactors. In newly constructed landfills, thermocouples are generally added to every other lift with a minimum of one per two acres. Temperature serves as an indicator of biological activity and as a fire prevention tool in the event of excessive temperature increase.

5.7.3.2 Cellulose/Lignin

Cellulose and lignin are found in wood and paper products associated with solid waste. Cellulose is readily degradable under anaerobic conditions while lignin degrades quite slowly. Fresh waste can be expected to have significant amounts of cellulose. The percent cellulose will decrease as the landfill ages while lignin will remain constant or decrease very slowly. The analysis of cellulose and lignin (C/L ratio) in waste has traditionally been used to determine the stability of solid waste and has been shown to be a reliable indicator. Research suggests that the C/L ratio is high in fresh waste and decreases dramatically with waste age. Unfortunately, while the analysis is very time consuming and expensive, volatile solids may be substituted.

5.7.3.3 Volatile Solids (VS)

This analysis is a very inexpensive measurement of the amount of biodegradable material that is remaining in the waste mass. The test consists of the high temperature destruction (55° C) of volatile organics determined before and after sample weights. Volatile solids results have been shown to correlate linearly with cellulose and cellulose/lignin data (Ham, 1987). Moreover, the analysis is about 10% of the cost of the cellulose/lignin analysis. In high plastic content samples the values are sometimes slightly inflated. Fortunately, the technique is inexpensive enough that sufficient replicates could be taken to obtain statistically sound data.

5.7.3.4 Biochemical Methane Potential (BMP)

BMP (Hilger and Barlaz, 2000) is a measure of the volume of methane that can be produced per gram of solid waste under optimum conditions in the laboratory. This is a direct indicator of the amount of residual biodegradable material in the solid waste. This test appears to be extremely important when evaluating complete stabilization and landfill closure. BMP coupled with Volatile Solids should give a total measurement of the residual biodegradable mass.

5.7.3.5 Moisture Content:

Moisture content is important for the prediction of how much water is still needed and if the distribution of liquids is adequate. There is promise that in-place moisture meters will some day replace this test. A large sample size is important to avoid inaccurate laboratory analysis.

5.7.3.6 pH

Field pH measurement of trash directly upon sampling is a valuable tool for the measurement of the stage of landfill biodegradation.

5.8 Gas Parameters

The addition of moisture to solid waste is expected to result in the rapid onset of methanogenesis and increase volumes of methane in a shorter amount of time when compared to the previously used dry entombment methodology. The in-line monitoring of methane, carbon dioxide, and oxygen will allow not only the determination of percentages and volume of each gas, but will give immediate recognition of the actual phase of biological activity that is occurring in the landfill. Carbon dioxide (CO_2) is a good indicator of landfill fires as well. Additional testing for NMOC, HAPs and SEM supported by research utilizing flux boxes or open path FTIR can be used to demonstrate the positive aspects of moisture addition with regard to atmospheric environmental protection through reduced emissions and shorter operation times due to early closure.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The ITRC ALT team recognizes that incorporating bioreactors into conventional landfill operations is a relatively new and innovative practice. There are a variety of research projects underway to evaluate design, construction, operation, and closure practices related to bioreactors. While bioreactors may have several advantages as discussed in Section 1.3, the waste industry is still learning much about the full scale operation of bioreactors. This is why the ALT team recognizes the process of “the learning bioreactor” as identified in Figure 1-2. The continued successful operation and optimization of bioreactors is an iterative practice.

Bioreactor advantages as conclude in this document include:

- Efficient utilization of permitted landfill capacity by creating reusable air space
- Stabilization of waste in a shorter time, thereby reducing the potential release of constituents from the landfill
- Reduced leachate handling cost by reusing the leachate in a leachate recirculation program
- Reduced post closure care by increasing the stability of the landfill and its constituents and reducing the threat associated with potential release of constituents from the landfill. This could translate into modification or termination of the post-closure care regulatory requirements and ultimately custodial care as defined in ITRC’s ALT-4 2006 (in progress).
- Optimization of waste emplaced in a landfill
- Landfill gas as a revenue stream. While both conventional and bioreactor landfill can generate gas, bioreactors have the potential to generate gas at a greater rate and by using more of the available gas generating material in the landfill. Appropriate collection and management of the gas can generate more revenue quicker than conventional landfills. This in turn may increase the economic viability of whether to utilize the gas generated as a valuable commodity.
- Reduced air emissions containing VOC and HAPs by the degradation of constituents into less noxious forms of the source chemicals. This could result in reduced post-closure care requirements once the gas emissions are within regulatory limits.
- Gaining advantage from alternative cover designs by being amenable to covers that are less prone to failure due to differential settlement. One key to the bioreactor process is to

recognize that alternative cover designs and gas collections process are not mutually exclusive.
- Reduced toxicity of leachate and waste material through the stabilization, degradation and/or sequestration of constituents in the waste; some of which could migrate and become entrained in the leachate. Studies have shown that bioreactor leachate contain reduced concentrations of constituents over time, until the leachate ultimately achieves applicable drinking water constituent concentrations. This could translate into reduced post-closure care requirements.
- Consistency with sustainable landfill design where the sustainable landfill concept blends the act of allowing or encouraging the in-place waste to degrade (organics) and chemically bind (inorganics) and then mining the degraded material for recovery and reuse.

Other conclusions and recommendations identified in this guidance include:

- The application of bioreactor technology at an unlined landfill is difficult from a regulatory perspective because liquid addition is prohibited in an unlined landfill. There may be unusual exceptions where naturally occurring shale or clay formations might be construed as an adequate liner, however it may be:
  - regulatorily impractical and expensive,
  - geologically rare and expensive, and the
  - engineering is expensive
- One of the most important factors for optimal bioreactor performance is the uniform and continuous distribution of moisture within the waste mass.
- Liquids recirculation should be initiated only when the gas venting system is constructed and operating. Gas collection should be designed to work with leachate collection and recirculation systems. Bioreactor landfills should be designed and constructed to allow gas recovery coincident with the beginning of landfill operation.

In addition, The ITRC ALT team believes that bioreactors can

- expedite beneficial reuse of landfill capacity, resources, and expedited reuse of the property,
- manage and reduce threat from MSW, and
- reduce or eliminate the carbon source in MSW.

Choosing the proper analytical tools for demonstrating stabilization in moisture enhanced landfills is critical. This is presently believed to primarily require the measurement of multiple parameters involving both carbon and nitrogen. The analyses required involve all three media found in the landfill environment. These are the solid, liquid, and gaseous phases. Obviously, the costs involved are great. Therefore, the goal of the ongoing research and development effort is to show that conventional, cost-effective laboratory analyses can be used to determine the rate and endpoint of stabilization. Data collected to date suggests that the pH, moisture content, volatile solids and density of the solid waste may provide the required information when compared to COD/BOD and nitrogen values in the leachate and gas volume and composition over time. This must be proven through the collection of all the discussed analytical parameters and the demonstration of a statistical correlation between the various analytical methods.

The post-closure care regulatory requirements of bioreactors are the same as those for conventional landfills. However there will likely be operational differences in Closure and Post-Closure Care of a bioreactor. The team recommends that final closure not be initiated until operation of a bioreactor and utilization of available air space is completed.

7.0 POST CLOSURE CARE

The post-closure care regulatory requirements of bioreactors are the same as those for conventional landfills. However there will likely be operational differences in Closure and Post-Closure Care of a bioreactor. The team recommends that final closure not be initiated until operation of a bioreactor and utilization of available air space is completed. The general requirements include the protection of human health and the environment by not allowing the wastes isolated in the landfill to release into the environment. Bioreactors are more dynamic than conventional landfills, and certainly will undergo more changes than a conventional landfill. However, one of the goals of bioreactors is waste stabilization.

Waste stabilization can include the long term structural stability of the landfill via degradation of the waste materials. Stabilization can also be manifest by the reduction of constituents detected in the leachate. This leads toward an evaluation of real threat associated with the bioreactor following closure. The ITRC's Technical and Regulatory Guidance for Ending Post-Closure Care at Landfills (ITRC ALT-4 in progress) describes a methodology to evaluate the stabilization of landfill material.

8.0 STAKEHOLDER INPUT

Community stakeholders should be involved at early stage of considering the use of bioreactors. Experience has shown projects benefit from stakeholder input and the earlier that input is received the more they feel ownership of the outcome. While outreach efforts may exceed the specific regulatory requirements, they offer a more cooperative partnering between the facility, the regulatory oversight authority, and the community. Thus, community involvement should be planned, executed with assurances, and expectations are well defined.

Community stakeholders can include local, state, and federal government officials, representatives of affected tribes, Non-Government Organizations (NGOs), neighborhood action committees, or a citizen of the surrounding community. In the planning of bioreactors and the associated post-closure property redevelopment conservation groups, community planning groups, wildlife preservation and management groups should always be offered input into the consideration of potential ecological elements and the resulting habitat it may creates following closure of the bioreactor. This involvement should address minimally the local, state, and federal laws, regulations, ordinance, guidance, and policy and planning provisions for community. Efforts beyond specific mandates will be valuable. Enhanced community involvement will lead to better, more acceptable and defensible solutions and expedite site land reuse and the ultimate management of post-closure care risks. One of the objectives of the responsible parties should be to integrate community stakeholders into all of their processes since stakeholder discussions can clearly influence specific cleanup goals and use criteria.

When land use changes and the potential risk associated with the reuse modifications are re-evaluated, community stakeholders should be offered the opportunity to be involved and make their issues, needs, and concerns part of the modification outcome. The process, potential technologies and alternatives analysis, should be made easily available for community review and input. The community's involvement in answering the obvious question "Will it do any harm?" can be substantive. This question must be addressed carefully and honestly.

Examples can be cited where this open process has been used documenting successes or failures in particular situations. In the case of an evolving process and management system, one may propose a solution believed to be likely to work, but has not been tried in a comparable situation. In such a situation, accurate, complete, and clear information must be available. Explain why the process and technology is likely to work and describe the causes of possible failure scenarios.

The following must be reviewed:

- How likely is a bioreactor to fail?
- What is the consequence of that failure?
- Discuss contingent alternatives.

Community stakeholders will embrace an opportunity to apply a new solution to a situation, particularly if there is a good likelihood that it will succeed; it benefits their community and offers more appealing use of the property following completion. Be open about the potential risks and benefits. The community must be offered the opportunity to weigh the potential risks against the potential benefits, since they are most directly affected by the contamination and by the success or failure of the technology. In certain cases, they are also the ones who bear the cost of the cleanup or, at the very least, as taxpayers in practice serve as the insurer of last resort.

In 1997, the State and Tribal and Government Working Group (STGWG), working with the U.S. Department of Energy (DOE) Office of Science and Technology, developed a set of principles for the integration of tribes and stakeholders into the process of evaluating and developing new technologies for the treatment of mixed low-level waste. Below is a discussion of the applicable STGWG principles and how they could translate to a situation where in landfill bioreactor operation and post-closure care changes are being considered.

- Minimize effluents—Stabilize waste as quickly as possible. Avoid the generation of reaction side products and new contaminants.
- Minimize effects on human health and the environment—Protect present and future drinking water supplies. Minimize the potential for accidents.
- Minimize waste generation—minimize the production of waste from landfills.
- Address social, cultural, and spiritual considerations—Minimize land use and habitat destruction. Discuss the transport of chemical reagents with tribes and stakeholders and adapt such transport to address their concerns. Respect the social, cultural, and spiritual values of specific sites. Protect local vistas. Minimize noise and traffic as well. Include the costs of tribal and stakeholder participation in cost estimates and budgets. Also, include the costs of compliance with intergovernmental agreements in cost estimates and budgets. These cost

estimates may also include evaluations of the energy use throughout the remedy's life cycle. If possible, these could include comparative landfill operations that are presented at stakeholder meetings.

- Provide timely, accurate, complete, and understandable information in a time frame to consider prior to final decisions and determinations so stakeholders may have an impact on the decisions. Provide information about any previous applications of the technology. Provide information about the hazards and risks and also potential hazards and risks, as well as benefits and potential benefits. These evaluations could include impacts on local and private wells, transportation, dust, odor, noise, and air buffer zones. Keep the tribal and stakeholder representatives involved and informed throughout the evaluation, selection, permitting, construction, and operation processes. The upper levels of management of the company implementing the remedy need to understand the community concerns and be vested in addressing their concerns. Independent technical advisory resources should be made available to the tribes and stakeholders whenever feasible.
- Incorporate tribal and stakeholder involvement into the permitting process, and the performance evaluation of site.

When an evolving process such as progressive and modified landfill construction, operation, and ultimately potential post-closure care is considered for application to a waste containment situation, there are uncertainties about the efficacy and threats of the technology in a given situation. Public acceptance of new processes and technologies is more likely if tribes and stakeholders are involved in a timely and meaningful manner in the evaluation process. Such involvement will enable the early identification of significant issues and the joint resolution of these issues. In turn, public involvement promotes faster and more efficient acceptance of innovative operations, closure or post closure care practices.

One of the foremost challenges in getting bioreactors considered is that all the participating stakeholders need to recognize that their respective roles in the process sometimes are in conflict and sometimes are congruent. Some of the greatest opportunities for win-win solutions usually emerge when the participants choose an approach based on mutual respect, building trust, and above all being open to new approaches and the creativity than often springs up in groups operating outside the limits history has given them by example.

In the team's attempt to think through this integration of stakeholders into creative and problem solving teams we offer the following table (Table 8-1) which summarizes who the stakeholders are and how they can participate in the solutions to MSW

Table 8-1. Stakeholders

STAKEHOLDER	CONTRIBUTION	IMPORTANCE	INTEREST
State and Federal Government Regulators	Enforcement, licensing, technical assistance, outreach, and education	Usually define the framework within which decisions are made	Training on green technologies and success stories
Industry	Site owner, principal source of cleanup funds, major stake in re-use decisions, receptive to community goodwill and benefits from their support	May control opportunity for land redevelopment, early involvement may improve quality of results & economic benefits	Regulators should be aware of regional land use needs and communicate opportunities to industry.
Local community -as a whole as well as organized community and business groups	Community acceptance and potential active support to other project participants in considering new landfill approaches	Could make the economic and political difference in whether a bioreactor is a real option for the site	Meetings with community leaders, local media coverage well before key decisions are made
Environmental non-governmental organizations	Can provide third party accreditation, source of expertise in wildlife habitat issues and assessments, facilitation of projects, volunteer labor, and political advocacy for re-use options	Can augment and/or stimulate local community initiative and can potentially facilitate community outreach and participation where applicable	Local community leaders should initiate contact with these groups
Consultants	Key technical advisor and project planner for site owner and project contractors	With regulators, they define the framework within which decisions are made	Training and education on bioreactors
Academics	Source of expertise for technology applications and wildlife habitat issues as well as network to similar projects elsewhere, and voluntary labor	Especially valuable in helping project consultants keep current on new approaches	Early involvement helps overcome erroneous perceptions about technical and economic constraints
Philanthropic Foundations	Potential source of funds and project credibility for reuse options	Can augment and/or stimulate local community initiative	Early involvement improves likelihood of meeting Foundation criteria

All the entities described above have important roles in the overall MSW management process. However, if bioreactors are to become a viable possibility, the team believes that early and significant involvement by the local community and relevant NGO's is critical to both initial success and the ultimate sustainability of the site ecological end use.

The ITRC Alternative Landfill Technology team observes there are some common threads in successful ecological land re-use applications for site cleanups. They are:

- Technically sound methods for landfill closure and post-closure
- Bioreactor landfills as a design component
- Credible third party respected by all stakeholders
- All Stakeholders are involved

- Clear opportunities for the community to use the project/participate in the demonstration
- Efforts made by the industry and stakeholders was voluntary
- Trust established early on

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Appendix A

Acronyms

ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ACAP	Alternative Cover Assessment Program
AFC	alternative final cover
ARAR	applicable or relevant and appropriate requirements
ASTM	American Society for Testing and Materials
Bcy	bank cubic yard
BCM	biochemical methane production
BOD	biochemical oxygen demand
CEC	cation exchange capacity
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFM	cubic feet per minute
CFR	Code of Federal Regulations
C/L Ratio	cellulose/lignin ratio
COD	chemical oxygen demand
CQA	construction quality assurance
DOE	U.S. Department of Energy
DSA	design sensitivity analysis
EG	emission guidelines
FML	flexible membrane liner
FR	Federal Register
FTIR	Fourier Transform Infrared Spectroscopy
GPS	global positioning system
HAPs	hazardous air pollutants
HH&E	human health and the nvironment
ITRC	Interstate Technology & Regulatory Council
LFG	landfill gas
LCRS	leachate control and removal system
MQA	manufacturing quality assurance
MQC	manufacturing quality control
MSR	modified surface runoff
MSW	municipal solid waste
MSWLF	municipal solid waste landfill
NGO	non-governmental organization
NMOC	Non-methane organic compound
NRCS	Natural Resource Conservation Service
NSPS	new source performance standards
ORP	oxidation reduction potential
PCC	post closure care
POTW	publicly owned treatment works
QA	quality assurance
QC	quality control
RCRA	Resource Conservation and Recovery Act
RD&D	research development and demonstration
RMA	Rocky Mountain Arsenal
Scfm	standard cubic feet per minute

SEM	scanning electron microscope
TDS	total dissolved solids
TKN	total kinetic nitrogen
TOC	total organic carbon
TS	total solids
TSS	total suspended Solids
TSWG	Tribal and Stakeholder Working Group
TVA	total volatile acid
USACE	U.S. Army Corp of Engineers
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VFA	volatile fatty acid
VOC	volatile organic compound
WMU	waste management unit

Appendix B

Glossary

GLOSSARY

acidogenic bacteria. Bacteria that consume the soluble organic material and converts it to TVAs.

field capacity. For bioreactors, this is when the waste material is below saturation, but is not free draining.

aerobic. In an aerobic bioreactor landfill, leachate is removed from the bottom layer, piped to liquids storage tanks, and re-circulated 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.

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

hybrid (aerobic-anaerobic). The hybrid bioreactor landfill accelerates waste degradation by employing a 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

sustainable landfill. Following degradation the permitted space is available for continued use as a landfill.

Appendix C

EPA RD&D Rule

EPA RD&D RULE

Research, Development, and Demonstration Permits for Municipal Solid Waste Landfills

Final Rule - March 22, 2004

Summary of Final Rule

EPA is revising the Criteria for Municipal Solid Waste Landfills (MSWLF) to allow states to issue research, development, and demonstration (RD&D) permits for new and existing MSWLF units and lateral expansions. This rule will allow Directors of approved state programs to provide a variance from certain MSWLF criteria, provided that MSWLF owners/operators demonstrate that compliance with the RD&D permit will not increase risk to human health and the environment over compliance with a standard MSWLF permit. EPA is finalizing this alternative permit authority to promote innovative technologies associated with landfilling of municipal solid waste. RD&D permits may provide a variance from existing requirements for run-on control systems, liquids restrictions, and the final cover requirements.

- Federal Register - Final Rule

  PDF File - http://www.epa.gov/epaoswer/non-hw/muncpl/mswlficr/rdd-pre.pdf

  HTML Format - http://www.epa.gov/fedrgstr/EPA-WASTE/2004/March/Day-22/f6310.htm

- Fact Sheet: States May Issue Permit Variances for Municipal Solid Waste Landfills

  PDF File - http://www.epa.gov/epaoswer/non-hw/muncpl/mswlficr/rd&d-fs.pdf

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Appendix D

Field Capacity Calculations

FIELD CAPACITY CALCULATIONS

In present, three types of moisture content are used in landfill design (Qian et al., 2002). The first type of moisture content is defined as the percent by weight of water in the waste based on the dry weight of the waste. This dry gravimetric moisture content definition, commonly used in geotechnical engineering analyses, is written as

$$w_{\mathrm{d}} = (W_{\mathrm{w}}/W_{\mathrm{s}}) \times 100 \qquad (1)$$

where

w_{d} = dry gravimetric moisture content, %;
W_{w} = weight of water; and
W_{s} = dry weight of solid waste.

In some references, moisture content is defined on the basis of wet weight of the wastes (i.e., w_{w}), written as

$$w_{\mathrm{w}} = [W_{\mathrm{w}}/(W_{\mathrm{s}} + W_{\mathrm{w}})] \times 100 \qquad (2)$$

where

w_{w} = wet gravimetric moisture content, %;
W_{w} = weight of water; and
W_{s} = dry weight of solid waste.

This can be somewhat misleading in that it gives moisture content values much lower than those computed based on dry weight (i.e., in Equation 1).

The third type of moisture content is defined as the percent by volume of water in the waste based on the total volume of the waste. This volumetric moisture content definition is widely used in hydrology and environmental engineering analyses. Mathematically,

$$\theta = (V_{\mathrm{w}}/V) \times 100 \qquad (3)$$

where

θ = volumetric moisture content of solid waste, %;
V_{w} = volume of water; and
V = total volume of solid waste.

The volumetric moisture content is used in many EPA documents regarding landfill design, construction, and operation and HELP Model.

If the moisture content is known by either a weight or volume basis, the following equations can be used to convert dry or wet gravimetric moisture content to volumetric moisture content or vice versa:

$$w_d = \frac{w_w}{1 - w_w} = \frac{\theta \cdot \gamma_w}{\gamma - \theta \cdot \gamma_w} \tag{4}$$

$$w_w = \frac{w_d}{1 + w_d} = \frac{\theta \cdot \gamma_w}{\gamma} \tag{5}$$

$$\theta = \frac{w_d \cdot \gamma}{(1 + w_d) \cdot \gamma_w} = \frac{w_w \cdot \gamma}{\gamma_w} \tag{6}$$

where

w_d = dry gravimetric moisture content of solid waste;
w_w = wet gravimetric moisture content of solid waste;
θ = volumetric moisture content of solid waste;
γ = unit weight of solid waste, lb/ft^3 or kN/m^3; and
γ_w = unit weight of water, 62.4 lb/ft^3 or 9.81 kN/m^3.

Appendix E

ITRC Team Contacts, Fact Sheet, and Product List

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