

VOLUME 8

Deliverables to meet work plan objective 7: Develop standardized design and operation procedures for this technology

8.1 Objective 7 of the project work plan was:

Develop standardized design and operation procedures for this technology.

The work plan identified the following methodology to meet objective 7:

The data collected from the study will be used by the researchers to develop standardized design and operating procedures. This will also include the collection of data to allow the development of engineering models for bioreactor landfill simulation. Design procedures include the design of injection and extraction wells, spacing of such wells, design of leachate collection systems in bioreactor landfills, and the design of a gas collection cap.

The deliverables identified in the work plan included:

- *Models for use in generating protocols for standard operating procedures*
- *Standard Operating Procedures*
- *Models for use in simulating physical, chemical, and biological processes occurring in landfill bioreactor*
- *Presentation of data in periodic reports*

8.2 Design and Operation of Bioreactor landfills

Although the US Subtitle D landfill regulations permit leachate recirculation in landfills with composite liners, some of the state regulations do not allow the liquids addition to the extent needed to reach desired bioreactor conditions due to concerns with the lack of accepted design and operational guidelines. Operating a MSW landfill as a bioreactor does have multiple potential advantages, both from an economic and an environmental perspective. It is equally true, however, that greater environmental (and economical) disaster can result if a bioreactor landfill is poorly designed or operated. Concerns from mismanaged systems include slope failures, an increase in uncontrolled gas emission, leachate seeps and uncontrolled off-site migration of leachate. Thus it is critical that sound design and operational practices be established. This report provides design and operating procedures from the lessons learned from operating the NRRL bioreactor of the Florida bioreactor demonstration project.

8.3 Design procedures

A major project goal was to advance the understanding of bioreactor landfills in a manner that supports the development of standardized design techniques. While the many complexities associated with landfills and the long time-scale associated with obtaining data from operating landfills precludes the developments of one standardized design techniques for this technology, major contributions were made in this project. These include:

- An understanding of the movement of moisture within a landfill as a result of a particular liquid addition device (e.g. vertical well, horizontal trench) and application conditions (e.g. flowrate, pressure).
- An understanding of how landfill gas impacts moisture movement and how landfill gas collection differs in wet landfills relative to traditional landfills.
- The simulation of landfill processes through models including liquid flow, gas flow, and biological conversion.

Design techniques and considerations were discussed with interested parties throughout the project period. For example, refer to appendix H and the presentation materials of the 2004 workshop held by the project. Specifically the following lessons discussed design techniques and concepts.

- Power point presentation on “Moisture management” at the 2004 bioreactor workshop in Gainesville (Appendix H)
- Power point presentation on “Bioreactor landfill design” at the 2004 bioreactor workshop in Gainesville (Appendix H)
- Power point presentation on “Management of gas at wet landfills” at the 2004 bioreactor workshop in Gainesville (Appendix H)

The following table 8.1 contains major design elements and how they impact the operation of a bioreactor.

Table 8.1 Major design elements and the impact on bioreactor operation

Major Design Elements	Impact of Bioreactor Operation and Liquids Introduction
Foundations	The increased unit weight of the waste created by the introduction of liquids and by the more rapid stabilization of the MSW can impact the earthen foundation upon which the landfill is constructed. The designer should factor this unit weight into design of the landfill foundation. Greater slopes may be required for gravity drainage to ensure that sufficient slopes exist after foundation settlement.
Liner systems	The type of liner system selected should factor in the larger amounts of leachate that are expected to be produced, and possibly increased temperatures resulting from accelerated biological activity (especially if air is added)
Leachate collection systems	The leachate collection system needs to be designed to accommodate the larger volumes of leachate that may be generated as a result of liquids introduction. Other design elements, such as foundation settlement and gas extraction system design should be considered. A well-designed and operated leachate collection system is one of the most critical features of a bioreactor landfill.
Storm-water control systems	The possibility of surface seeps as a result of liquids introduction should be considered in the design of storm water collection systems. Systems designed to mitigate and control seeps can minimize impact on storm water run-off.

Slope stability considerations	The addition of liquids to landfills has the potential to impact the pore water pressure existing within the waste mass, which in turn can lead to changes in the shear strength of the waste and slope stability concerns. Waste characteristics may also change as waste decomposes as a result of liquids introduction. Designers should factor added water pressures into their slope stability calculations.
Leachate management systems	The recirculation of leachate will be a part of the liquids management system. Leachate storage volumes should be increased to accommodate the leachate flow rates. Leachate treatment technologies that complement bioreactor technology should be considered.
Gas extraction systems	Liquids introduction not only increases the rate of gas production, it also impacts the efficacy of many of the standard gas collection techniques (e.g., flooded gas wells). Gas collection systems need to be designed from the on-set to accommodate liquids introduction.
Capping and closure	In some situations, liquids introduction may still be practiced after the landfill has ceased accepting waste. The designer should consider strategies for closure that complement bioreactor activities.

Models can also provide valuable tools for design purposes. In the following two sections, highlights of two PhD dissertations produced as a result of this project are presented. Dr. Pradeep Jain investigated the use of vertical wells for leachate recirculation. His work included mathematically modeling leachate flow from wet wells and presented how such results could be used as designed. Dr Nitin Gawande developed a model to simulate biochemical processes of solid waste biodegradation. His work includes development of the numerical model BIOKEMOD-3P, which is an extension of the computer model BIOKEMOD. Using this he was able to simulate the experimental data of anaerobic biodegradation of solid waste in laboratory scale bioreactor. The model was also used to simulate simultaneous nitrification and denitrification processes in laboratory-scale microcosms.

8.4 Design of vertical wells leachate recirculation system

8.4.1 Mathematical modeling of fluid flow through vertical wells

Jain et al. (2007) mathematically simulated data on some of the key variables that could be used to design vertical wells for liquids introduction at bioreactor landfills. The data presented in this study were generated based on fundamental principles governing fluid flow in saturated-unsaturated porous media. The rate at which liquids can be added to a well and the lateral and vertical extent of liquids movement away from the well were examined as a function of media properties (porosity, hydraulic conductivity, anisotropy ratio), well dimensions (radius and screen length), injection pressure, and volume of liquids added. The results are presented in terms of dimensionless forms and could be

used to design (or analyze) a vertical well system for a wide variety of conditions (well dimensions, media properties, etc.) encountered in this type of system. The table 8.1 indicates the parameters used for numerical modeling.

Table 8.1 Parameters values used for numerical modeling

Parameter	Symbol
Waste	
Hydraulic conductivity,	K_r (cm/sec)
Hydraulic conductivity,	K_z (cm/sec)
Van Genuchten parameter,	α (m^{-1})
Van Genuchten parameter,	n
Porosity,	θ_s (Vol/Vol)
Residual moisture content,	θ_r (Vol/Vol)
Waste compressibility,	α_s (m^{-1})
Well and Water	
Landfill depth,	b (m)
Well diameter,	$2r_w$ (cm)
Well depth,	l (m)
Screen length,	l-d (m)
Flow rate,	Q (m^3 /sec)
Water compressibility,	α_L (m^{-1})
Dimensionless pressure head,	ψ
Radial distance from the bottom of the well to the boundary of the zone of impact	r_l
Anisotropy ratio of the waste	a
Dimensional radial flux	q_r
Downward vertical extent of moisture movement	z_l
Dimensionless time	τ

The simulation results indicate that the pore pressure of the waste near the well increased after liquids introduction began; waste away from the injection well maintained initial negative pressure until it was impacted by the added liquids. It was observed that the phreatic surface attained a steady state and did not expand further even with continued liquids introduction. Figure 8.1 presents the steady-state isobaric contours at the end of the simulation period. As anticipated, the pressure was maximum at the bottom of well (12.5 m); however, water pressure dramatically declined at locations away from the well. Even though a relatively large pressure is needed to achieve the modeled flow conditions, pressures are rapidly dissipated within the media.

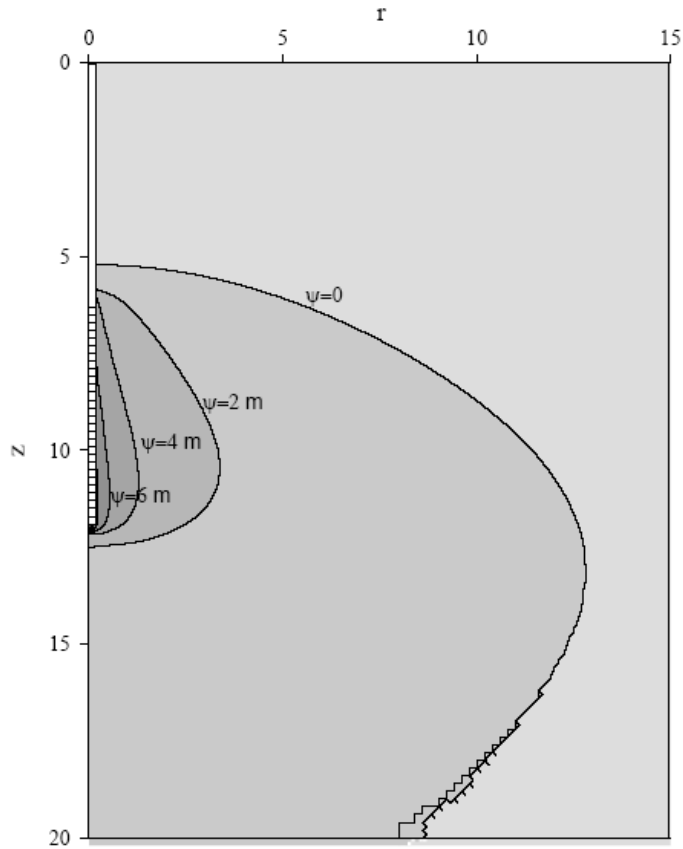


Figure 8.1 Pressure distribution at steady state for $Q=7.5 \times 10^{-5} \text{ m}^3/\text{sec}$ for an anisotropic media ($K_r=10^{-4} \text{ cm/sec}$ and $K_z=10^{-5} \text{ cm/sec}$) (Jain et al., 2005)

Figure 8.2 shows isoclines corresponding to the point where the degree of saturation has increased above the initial value (referred to throughout this paper as zone of impact); times corresponding to 50, 100, 200, 400, and 800 days are included. The results indicated that for this simulation, steady state was approached after 2.5 years. The time to reach steady-state depends on Q , K_z , and the vicinity of the well to the leachate collection system.

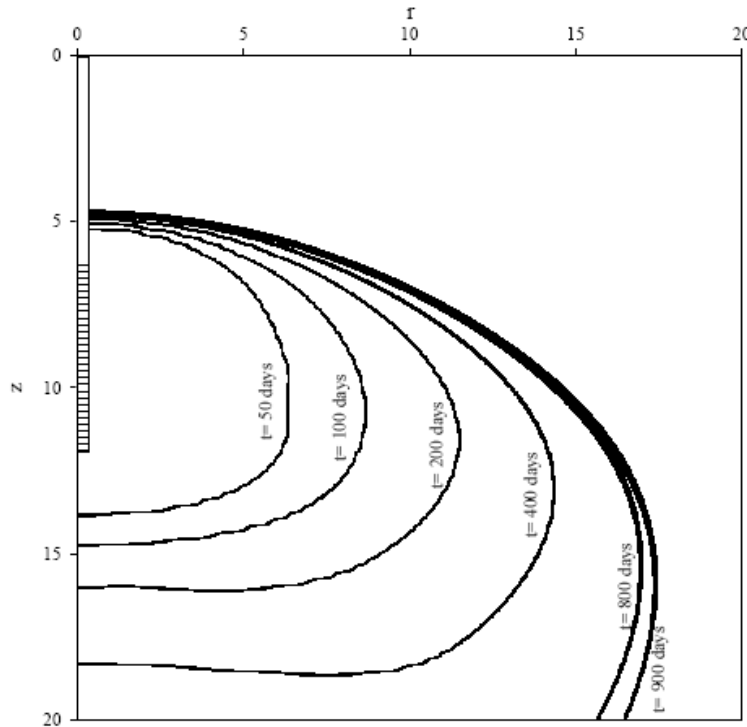
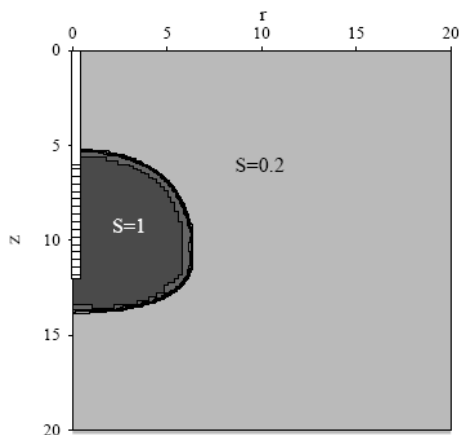
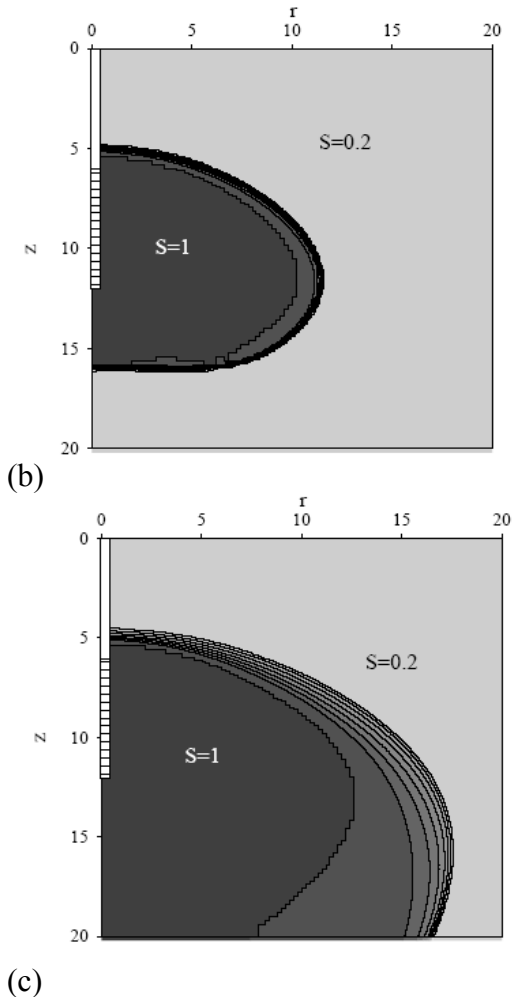


Figure 8.2 Example output from simulations showing zone of impact over time ($q_r=500$, $a=10$, $K10^{-5}$ cm/sec), Jain et al., 2007)

Figure 8.3 (a), (b), and (c) present saturation isoclines for several different degrees of saturation for the 2.5 year simulation at the end of 50, 200 and 800 days, respectively. In this simulation, the moisture moves as a relatively sharp wetting front during the initial stages of moisture addition (Figure 8.3 (a) and (b)). As the system approached steady-state (after 2.5 years), unsaturated flow outside the zone of saturation became more apparent (Figure 8.3(c)). For the majority of the simulation time, moisture moved as a sharp wetting front. Thus, the choice of the value of saturation isocline used to estimate to lateral or vertical movement should have inconsequential impact.



(a)



(c) Figure 8.3 Saturation profiles around a partially screened well (a) after 50 days, (b) after 200 days, and (c) after 800 days corresponding pressure distribution for $Q=7.5 \times 10^{-5}$ m³/sec (6.5 m³/day) for an anisotropic media ($K_r = 10^{-4}$ cm/sec and $K_z = 10^{-5}$ cm/sec)

Figure 8.4 presents the temporal variation of r_1/r_w for different q_r and a values. The anisotropy ratio was found to have a greater impact on the lateral movement than q_r . The ability of an anisotropic media to transmit flow in the radial direction is greater than that in the vertical direction and thus, a higher anisotropy ratio promotes greater lateral moisture movement. For a conservative system design, $a=1$ should be used in case it is not known. Figure 8.6 presents the temporal variation of the vertical extent of moisture below the well for a series of q_r and a values. The q_r values were found to have more significant impact on the vertical extent of moisture movement than anisotropy ratio. The maximum vertical extent of moisture movement was found to be 1.4 m below the well. The family of curves presented in Figures 8.4 and 8.5 can be used to estimate the extent of lateral and vertical moisture distribution for cases where q_r , a and τ are in the range used in this study. Details on this study can be found in the PhD dissertation of Jain (2005).

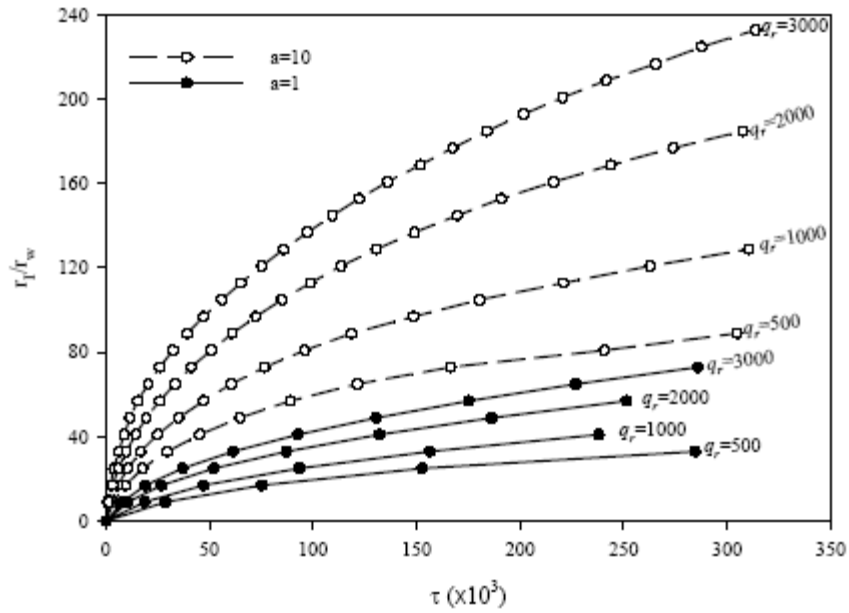


Figure 8.4 Temporal variation of dimensionless lateral extent (r_l/r_w) of moisture movement

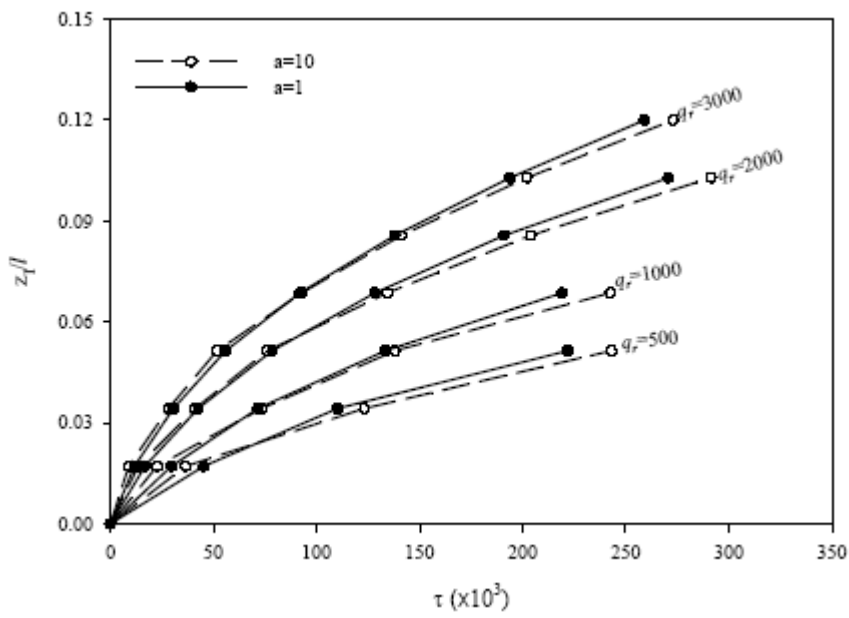


Figure 8.5 Temporal variation of dimensionless vertical extent (z_l/l) of moisture movement

8.4.2 Type of vertical well system

While designing the leachate recirculation system, it was hypothesized that with a single well screened across the landfill depth most of the liquid would flow through the bottom portion of the well due to greater water column head and would not be a good system for adding leachate to the upper waste layers. A cluster of three wells installed at different depths was chosen over a single well screened across the depth of the landfill in order to obtain a uniform distribution of leachate across the depth. It was found that the permeability of the waste at this site is reported to decrease with depth. The results of the injection tests at the NRRL indicate that higher leachate flow rate could be achieved through shallow wells than deep wells as also indicated by maximum achievable flow rates. Thus a single well screened across the depth of landfill could be sufficient for even distribution of moisture across the depth provided leachate recirculation is carried out at flow rates or pressures such that liquid level in injection well is at/above the screened section of the injection well as shown in figure 8.6.

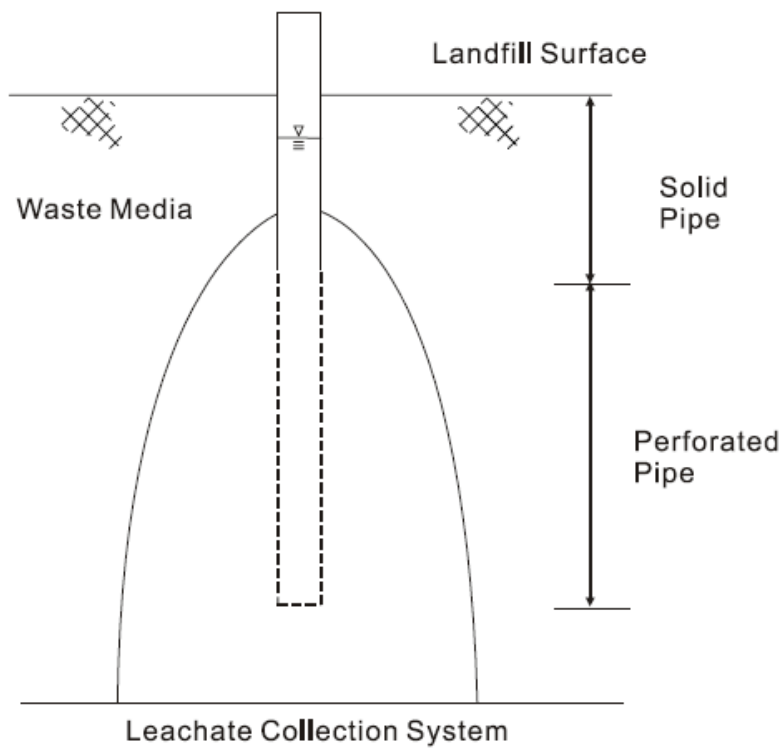


Figure 8.6 Schematic of a vertical well system

However, there may be scenarios where recirculation at lower pressure is desired, for example, injection near side slopes where high pore water pressure may potentially reduce slope stability and cause side seeps. A cluster of wells installed at different depth should be preferable over a single well for such cases. Moreover, if this system is also designed to add air to the waste a cluster of wells installed at different depths is recommended to achieve uniform distribution of air across the depth of landfill (Jain et al., 2004). The configuration (cluster of well or single well) of a vertical well system should consider other design parameters (such as pressure, flow rate) and functional requirements (air addition) as well.

Dissertations, Theses, and Projects:

Jain, P. (2005). "Moisture addition at bioreactor landfills using vertical wells: mathematical modeling and field application." Ph.D. Dissertation. University of Florida, Gainesville, FL.

Conference Proceedings

Jain, P., Townsend, T., and Reinhart, R. (2005). "Experiences from the operation of a full-scale bioreactor landfill in Florida." Solid Waste Association of North America's Wastecon 2005, Austin, TX, September 27-29, 2005.

Jain, P., Farfour, W., Jonnalagadda, S., Townsend, T., and Reinhart, D. (2005). "Performance evaluation of vertical wells for landfill leachate recirculation." Proceedings of Geo Frontier 2005, ASCE conference, January 24-26, 2005, Austin, TX.

8.5 Simulation and application of a multiphase microbiological and chemical kinetic-and-equilibrium model for simulating solid waste biodegradation

The biochemical models available to date for simulating solid waste biodegradation are able to handle only a limited number of species and reactions that are already defined in the model. There is no generalized model available to simulate user specified species and reactions or some often require minor modifications in the computer code. The model BIOKEMOD-3P was developed for simulating solid waste biodegradation, is an extension of models KEMOD and BIOKEMOD but for a three phase system. The chemical and microbiological reactions for a multi phase system are presented in this section. The governing equations describing the model are presented in the following section. The details of this model are present in appendix D of this report.

This model was able to simulate the experimental data of anaerobic biodegradation of solid waste in laboratory scale bioreactor. The model was also used to simulate simultaneous nitrification and denitrification processes in laboratory-scale microcosms.

8.5.1 Anaerobic Biodegradation of Solid Waste

The biodegradation of solid waste in laboratory scale bioreactor microcosms was presented by Barlaz¹ and to date it is one of the most comprehensive laboratory-scale studies of biodegradation of solid waste under anaerobic conditions. Therefore these data were considered for model application.

Figure 8.7 shows the comparison of gas composition from model simulation to that with the experimental data from Barlaz¹.

¹ Barlaz, M.A., Schaefer, D.M., and R.K. Ham (1989a). Bacterial population development and chemical characteristics of refuse decomposition in a simulated sanitary landfill, *Applied and Environmental Microbiology*, 55(1), 55-65.

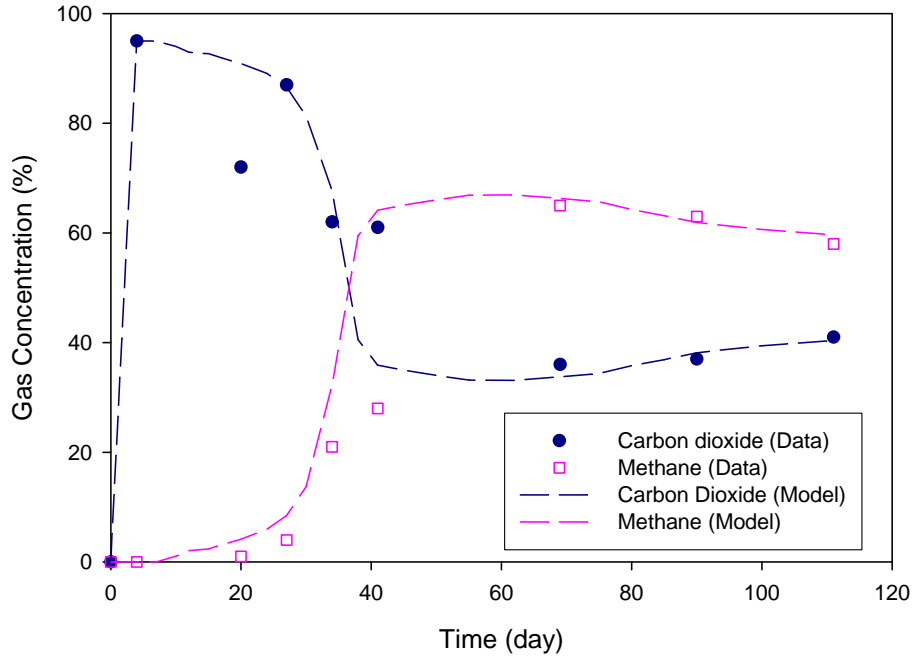


Figure 8.7 Comparison of model simulation

8.5.2 Nitrification and Denitrification Processes

The presence of ammonia-nitrogen in landfill leachate poses significant pollution risks. Simultaneous nitrification and denitrification processes may occur in bioreactor landfills under the conditions of limited carbon and oxygen conditions. Berge (2006) conducted a study with laboratory-scale microcosms for varying levels of ammonia nitrogen, oxygen content, and temperature.

The data from this study were simulated using the BIOKEMOD-3P model. Simulation results are presented and discussed in detail in Gawande et al. (2008b). Model simulations showed that simultaneous nitrification and denitrification occurred in the microcosm experiments. Figure 8.8 shows results from model runs of the fate of various nitrogen species in aqueous phase. BIOKEMOD-3P was successful in simulating the pH and it was highly sensitive to the nitrification and denitrification rates due to the changes in alkalinity. The variation of pH for the corresponding data set is shown Fig. 3. A plot of the mass of nitrogen in the gas phase is shown in Fig. 4. The kinetic parameters determined from the modeling experiment may provide valuable information for in situ nitrogen management in bioreactor landfills.

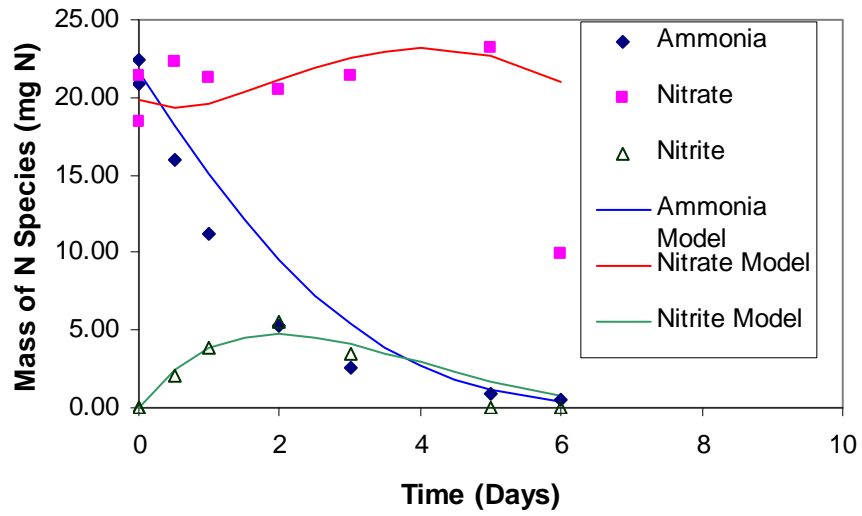


Figure 8.8 Plot of experimental data with model results for nitrogen species

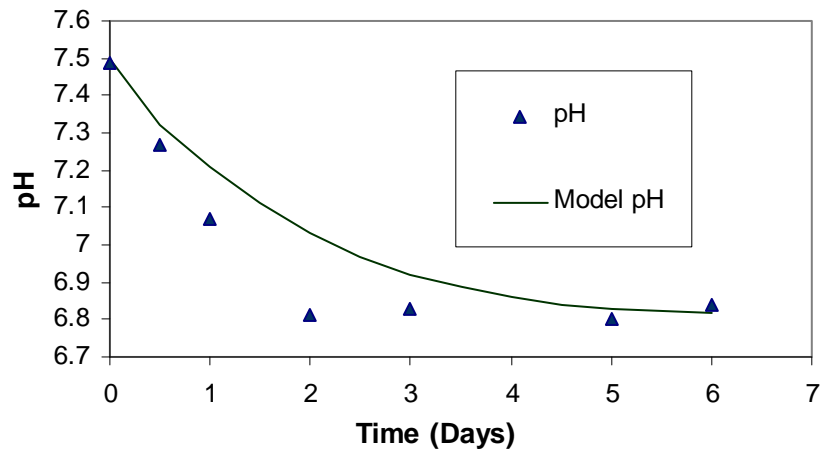


Figure 8.9 Plot of pH for experimental data and model results

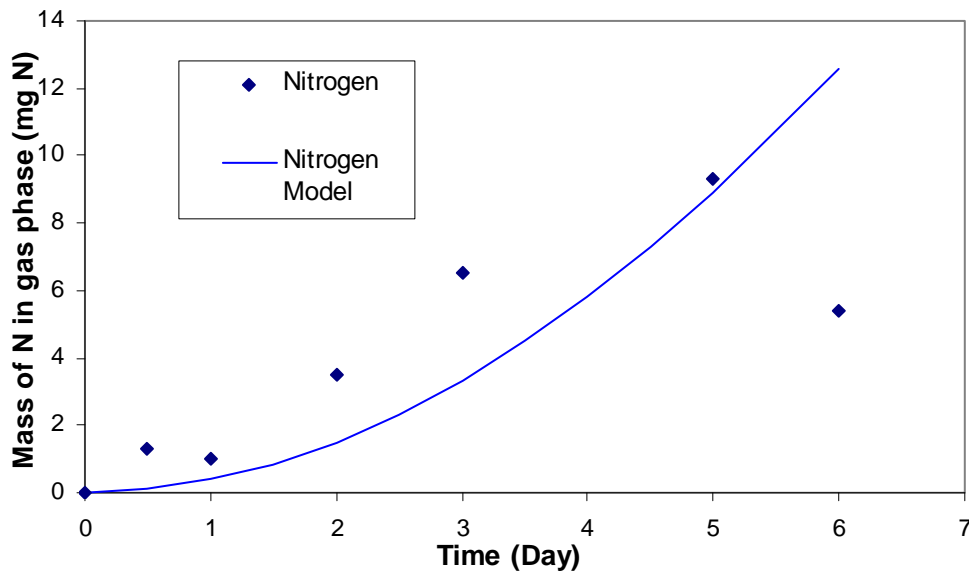


Figure 8.10 Plot of Nitrogen mass in gas phase for experimental data and model results

Peer-Reviewed Journal Articles

Gawande, N.A., Reinhart, D.R., and G.T. Yeh (2008a). Modeling biochemical process of solid waste biodegradation, part I: Development of a three-phase model, BIOKEMOD-3P, ready for publication.

Gawande, N.A., Berge, N.D., Reinhart, D.R., and G.T. Yeh (2008b). Modeling biochemical process of solid waste biodegradation, part II: Application of a three-phase model, BIOKEMOD-3P, ready for submission.

8.6 Standard bioreactor operating procedure

Bioreactor landfill is a new technology, and there are only a limited number of full scale bioreactor landfills in operation in United States or around the world. Bioreactor landfill operators encounter day to day problems in implementation, operation, and monitoring. So it is important to prepare a guide that can help bioreactor operators in their daily operations. One of the primary goals of the Florida bioreactor demonstration project is successfully operate and monitor the full-scale landfill bioreactor in Florida and create a guide for the landfill operators. This guide compiles the practical experience learned from the operation of the bioreactor landfill. The guide 'Bioreactor Landfill Operation: A Guide for Development, Implementation and Monitoring' has been compiled and is attached at the end of this volume. It is expected that this guide will be useful to all solid waste professionals, in particular, to the landfill operators. It has been prepared in a simplistic manner so that it can be useful to the landfill operators for their daily operations. This operator's guide contain fundamentals of bioreactor landfills, liquid and air addition, gas extraction system and monitoring of bioreactor landfills.

8.6.1 Best time to start a bioreactor

Bioreactor operations can be started as soon as possible following waste placement to ensure proper moisture content for waste biodegradation (may be after placement of first waste lift). The cell height shall be sufficient so that leachate or moisture addition is possible and the waste has enough capacity to absorb the moisture. Leachate shall be injected when arrangements have been made to capture the landfill gas. And, once gas production is well established, leachate recirculation can be introduced more frequently and at larger flow rates. To optimize the flow through the landfill and the impact area, the practice of short term high rate leachate recirculation may be best option during early stages so as to avoid lower back pressure and achieve high wetted area in the landfill.

High Oxidation reduction potential (redox potential) conditions associated with aerobic conditions provide for accelerated waste stabilization and reportedly improved leachate quality. So, high oxidation reduction potential can be considered as the best time to start bioreactor operations.

The bioreactor can be operated pretty well during the summers, at the temperature when microorganisms are quite comfortable and the stabilization process can start efficiently. At times when the temperatures are low (say below 50° F), it may be useful to inject air into the waste to increase the waste temperature. The air injection into the waste can “kick-off” the aerobic degradation of the waste, resulting in increase in the waste mass temperature. The air injection can be stopped and moisture can be introduced starting the anaerobic degradation process.

8.6.2 Bioreactor Fundamentals

There are three general types of bioreactor landfill configurations (US EPA, 2007):

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.

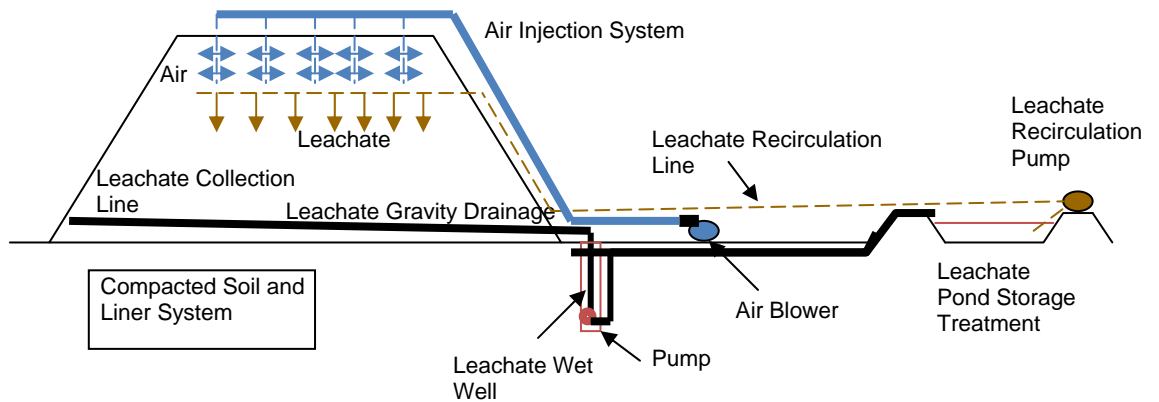


Figure 8.11: Schematic sketch showing an aerobic bioreactor

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.

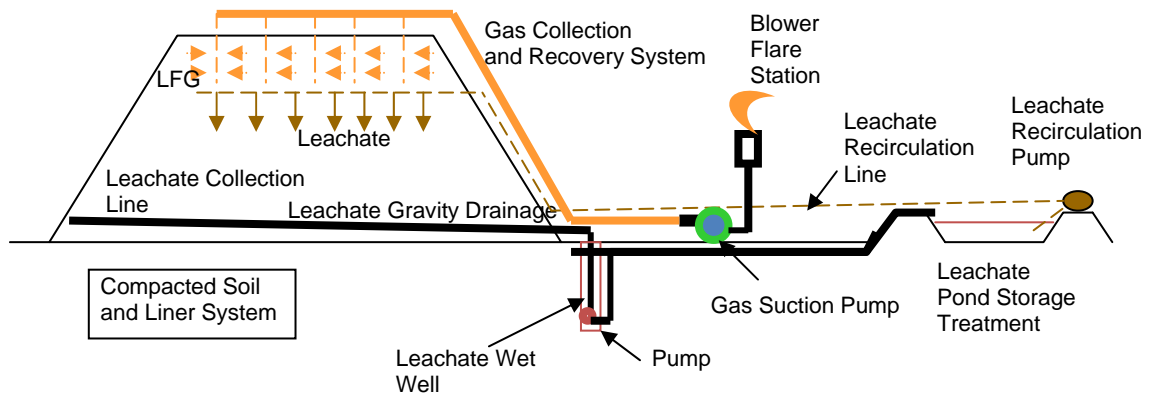


Figure 8.12 Schematic sketch showing an anaerobic bioreactor

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.

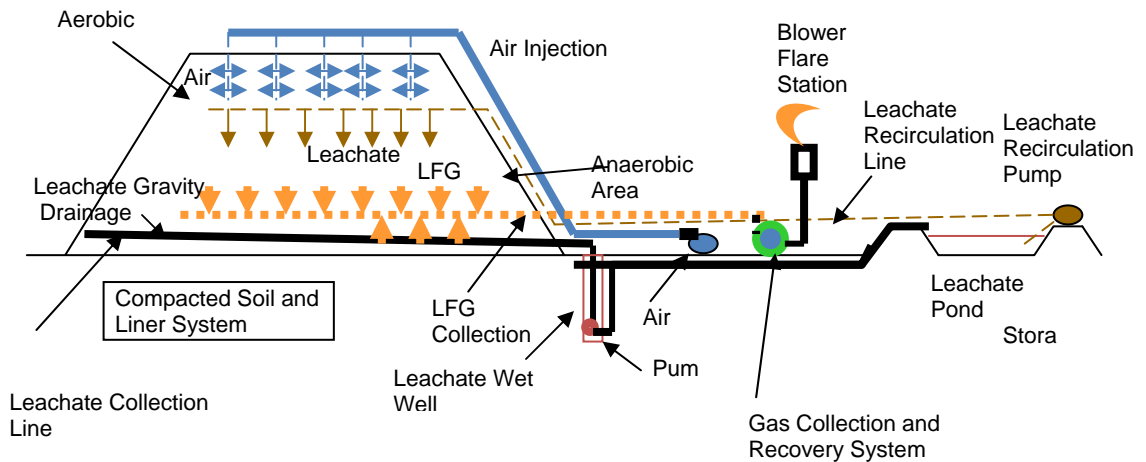


Figure 8.13 Schematic sketch showing a hybrid (aerobic-anaerobic) bioreactor

8.6.3 Moisture addition

Leachate recirculation is regarded as the most practical way to control moisture content in the waste. These systems can be broadly grouped into two categories depending on the way leachate is introduced into the waste mass: Surface leachate recirculation systems and sub-surface leachate recirculation systems. Leachate recirculation in a landfill can be done in several ways including prewetting, spraying, surface ponds, horizontal infiltration systems and vertical injection wells. Ground water can be added if leachate generated at the landfill is not enough for moisture addition.

- **Surface leachate recirculation systems**

Prewetting

This method moistens the waste before landfilling. It is simple, efficient and ensures uniformity but at the same time is labor-intensive, incompatible with closure and causes leachate blowing and compaction.

Spray irrigation

This technique sprays leachate on waste surface. It promotes evaporation and is flexible, but it may cause leachate blowing and misting, and is incompatible during closure of the Cell.

Surface Ponds

This involves removal of one or two layers of waste from the top of the landfill to introduce leachate. Using surface ponds leads to very effective wetting directly beneath the pond and provides for leachate storage, but it may collect stormwater, cause floating of waste and odor problems and is incompatible with closure.

- **Sub-surface leachate recirculation systems**

Vertical Injection Wells

This technique uses vertical pipes or wells to introduce leachate into waste mass. It facilitates recirculation of relatively large volumes of leachate using low-cost materials and is compatible with closure. Subsidence problems, limited recharge area and interference with waste placement operation are a few demerits.

Horizontal trenches

This technique involves horizontal infiltrator devices for subsurface introduction of leachate into the trenches dug into the waste. It has all the advantages of vertical injection wells but potential biofouling limiting the volume and subsidences affecting the trench integrity are feared.

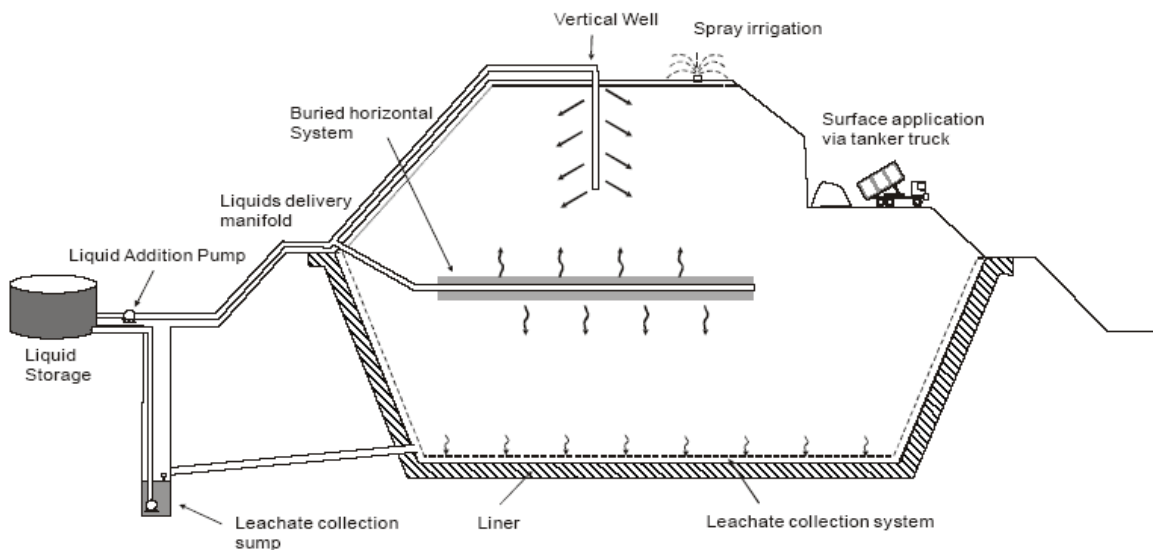


Figure 8.14 Various methods of liquid addition in a bioreactor

8.6.4 Air Addition

Air addition is practiced at some landfills for the purpose of achieving rapid waste stabilization. The aerobic conditions are created in the landfill by the addition of air that promotes organisms that can stabilize the waste more readily than anaerobic systems. The aeration of landfills is similar in concept to operate MSW compost plants. The aerobic process results in greater heat production and can thus lead to an increase in landfill temperature (above that seen in typical anaerobic landfills). Because of the amount of heat produced in aerobic systems, addition of air sometimes also result in drying out wet landfills. For the aerobic bioreactor, the balance of air and water is critical. Sufficient water must be available to provide a suitable environment for the microorganisms. If sufficient water is not available, excessive heat production can result in combustion of the waste. If water is available in excess, air cannot reach the waste due to physical barrier created by the water and the system will not run aerobically. Air addition can also be used to warm up cold landfills and preparing them for additional

anaerobic treatment. The following points summarize the fundamentals of operation for air addition.

1. Aerobic conditions are established by injecting air into one or more of the most recently placed waste lifts. The blower used for aeration should be capable of delivering from 0.01 to 0.06 standard cubic feet per minute (scfm) per bank cubic yard (bcy) of waste (scfm/bcy). A higher aeration rate (up to 0.06 scfm/bcy) may be 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.
2. Pulling oxygen through a cover system into a bioreactor landfill can be an alternate of air injection. Even though this allows all emission from a landfill to be captured it is prohibitively costly at a full scale.
3. In retrofit bioreactors, air addition is possible through vertical wells. 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.
4. For the retrofit bioreactors, the amount of organic material in the landfill is estimated to calculate the amount of oxygen required. This will help 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. The aerobic waste degradation increases the waste temperature significantly therefore constant temperature monitoring is required. The safe operating temperature range for the aerated waste is between 125° F and 170° F. The preferred operating range is between 145° F and 165° F. Temperatures at or above 170° F are a cause for concern. It is recommended that fire fighting material be procured in advance (e.g. water, foam suppression, or CO₂) be used to smother any fire; however water can create gases (vapor) that may cause explosive conditions. It is recommended that a fire department or fire suppression expert be consulted for any potential fire condition in a bioreactor. Once the waste temperature reaches $\geq 140^{\circ}$ F, a change in temperature of $\geq 20^{\circ}$ F in a 48-hour period calls for immediate action (ITRC, 2006).
6. Temperature monitoring at different locations of the bioreactor can be done by providing thermocouples at various strategic locations. Temperature higher than 170° F can be indicative of fire/ smoldering in the waste and the operator shall have temperature control plans developed for that. Temperature rise can be controlled by stopping air injection thereby cutting the source of oxygen, recirculating cold leachate and completely wetting the particular location.
7. CO concentration acts as an indicator of fire hazards and shall be monitored at the monitoring points close to the air injection wells. CO concentrations can be measured inexpensively with a Dragger tube in the field. The CO concentration at all the monitoring points shall stay below the standards set by local, state and federal regulations.

8. Each aeration pipe should be checked for blockage (watering-out) weekly. Checking the pressure and listening for surges is adequate.

8.6.5 Landfill Gas Extraction

Landfill gas (LFG) production is accelerated in anaerobic bioreactor landfills. The increase in gas production results from accelerated waste stabilization and due to the return of organic material in the leachate to the landfill that is converted to gas. Gas from anaerobic decomposition of waste is approximately 50: 50 by volume of methane (CH₄) and carbon dioxide (CO₂). Typical landfill gas has slightly more CH₄ than CO₂.

Different techniques may be used to collect LFG. Possible options include use of horizontal collection systems, vertical wells or surface trenches under the caps as shown in figure 8.15.

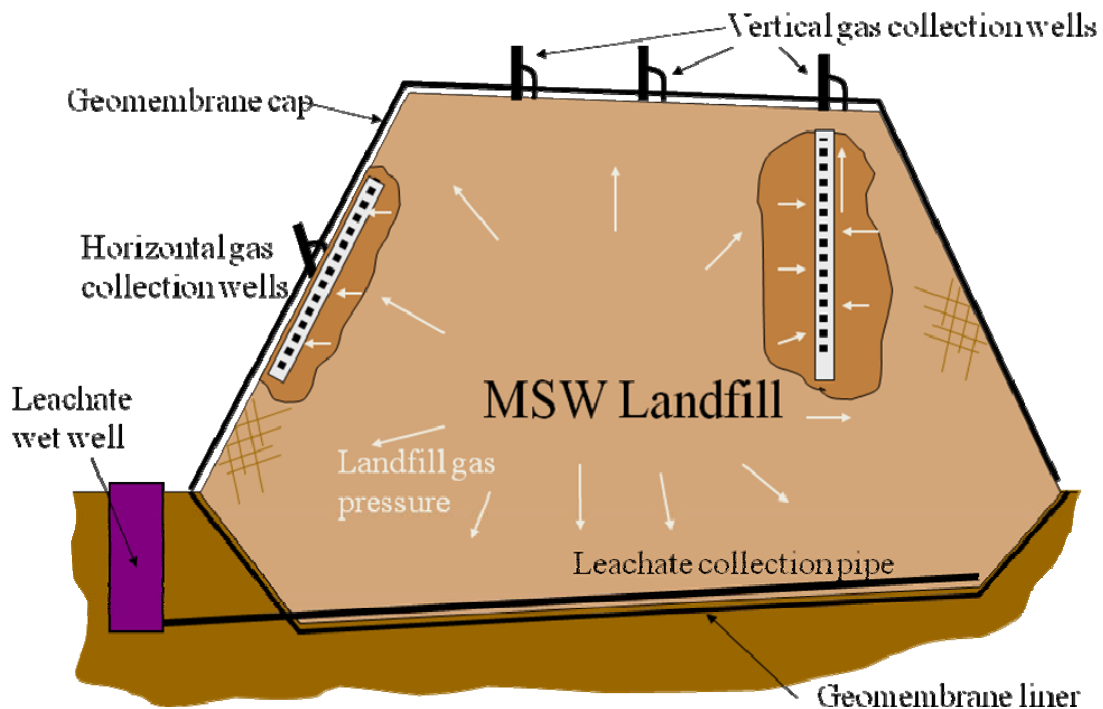


Figure 8.15 different configurations for gas collection system

Horizontal gas trenches are constructed in a similar way to the horizontal injection trench for liquid addition. LFG can be collected passively or actively. In a passive system the gas generated in the landfill will migrate toward a well under the pressure difference between the landfill interior and the gas well (atmosphere), thus creating a potential to remove gas from the landfill. Or alternatively in an active system, horizontal trenches or vertical wells are connected by a manifold to a mechanical blower as shown in figure 8.16. The blower induces a vacuum in the manifold and the wells or trenches, extract gas from the landfill interior. The vacuum has to be maintained in such a way so as not to draw air into the landfill.

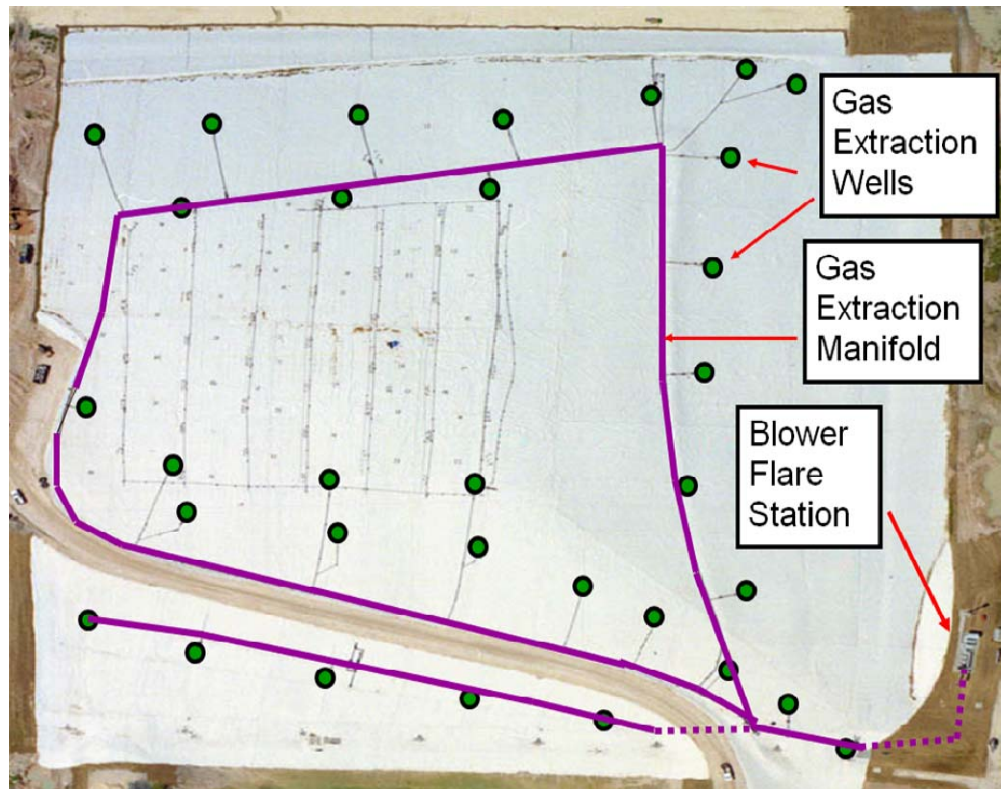


Figure 8.16 Gas collection system

The air drawn into the landfill may slowdown the methanogenic microbial activity and moreover gas quality may get worsened. The design engineer should take into account the fast decomposition rate in designing gas collection systems. Leachate recirculation in bioreactor landfill poses special challenges in designing landfill gas collection system. Accelerated gas production at wet landfills also results in several additional challenges for bioreactor operators. Based on these challenges, suitable gas collection strategies have to be adopted. Details on the monitoring of the gas collection system is mentioned in volume 3 of this report and the bioreactor operator's guide attached as an appendix along with this report.

8.6.6 Monitoring Parameters for Bioreactor Landfills:

There are key parameters, if examined closely, that will collectively ensure the optimal operation of bioreactor landfills and minimize risk to human health and the environment. Table 8.2 shows the parameters for mass loading calculations. Table 8.3 shows the parameters for monitoring moisture addition. Table 8.4 shows the parameters for monitoring the waste of the bioreactor landfills. Table 8.5 shows the parameters for monitoring the landfill gas.

Table 8.2 Mass loading calculation parameters

Parameter	Frequency	Units
Visual Landfill Inspection	Daily	
Mass of Landfilled MSW	Daily	MG (tons)
Mass of Landfilled C&D Waste	Daily	MG (tons)
Mass of Soil (other than daily cover)	Daily	MG (tons)
Type of Daily Cover	Daily	
Mass of Daily Cover	Daily	MG (tons)
Landfill Volume	Quarterly	m ³ (yd ³)
Settlement	Quarterly	m (ft)

Table 8.3 Bioreactor liquid addition monitoring parameters

Parameter	Frequency	Units
Volume of Leachate Added	Daily	L (gal)
Rainfall	Daily	mm (inch)
Volume of Outside Liquid Added (e.g., Groundwater, Industrial Waste Water)	Daily	L (gal)
Volume of Leachate Generated	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)

Table 8.4 Bioreactor landfill solids monitoring parameters

Parameter	Method	Frequency	Optimum Range [€]
Average Temperature	Thermometer	Once every 18 months	35 - 55 °C
Average pH	EPA ^a 9045C	Once every 18 months	6.5 - 7.6
Average Volatile Solids (% M/M)	EPA ^b 1684	Once every 18 months	Decreasing Trend
Average Wet Based Moisture Content (% M/M)		Once every 18 months	< 35 %

Table 8.5 Primary bioreactor landfill gas monitoring parameters

Parameter	Flow	Frequency	Optimum Range
Total Gas	Orifice plate / Mass flow meter (scfm)	At least once a week	
Carbon Dioxide	Portable gas analyzer (% V/V)	Weekly	35-40
Oxygen	Portable gas analyzer (%)	Weekly	< 5

	V/V)		
Methane	Portable gas analyzer (% V/V)	Weekly	45 – 60
Carbon Monoxide	Portable gas analyzer (% V/V)	Weekly	≈ 0

Table 8.6 describes useful instrumentation for monitoring essential parameters at bioreactor landfills. Some of the instruments have been used for a long time, but some instruments are still in the stage of being tested.

Table 8.6 Landfill instrumentation for bioreactor project

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)	Using MTG Sensors. MTG Sensors use perforated pipe filled with gypsum or gravel with glass wicks for moisture transfer from surrounding waste to the media and measure resistance across the probe. Using TDR Probes: Moisture content is calculated using a fourth degree polynomial equation from the measured apparent dielectric constant (K_a)	As determined by budget permit requirements
Oxidation reduction Potential (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

8.6.7 Concerns during the operation of a bioreactor

Bioreactor landfills have great potential benefits, but at the same time it may be a cause of concern if the bioreactor operations like leachate recirculation and the addition of other bulk liquid waste to landfills are not performed correctly. A few of the more common concerns are described here. Possible methods of preventing and mitigating these concerns are also described here in brief.

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

Landfill Slope Stability: Since liquids are added in the bioreactor, internal pore water pressure increases and thereby decreases the shear strength of the waste, and thus endangers the landfill slope. The pore water pressure should be measured frequently to ensure that the liquid levels stay below a given level so as not to cause any threat to the landfill slope.

Availability of Leachate or Additional Liquids: Most of the times the leachate generated from the landfill may not be sufficient to meet the liquid requirement for recirculation into the bioreactor. So an operator may be required to arrange for additional liquids for recirculating into the bioreactor. Possible options include adding liquid from surface water ponds; groundwater; runoff water specifically collected for this purpose; leachate from surrounding landfills etc.

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

Odor Control: Odor can be a problem at some bioreactors. The anaerobic decomposition of waste results in formation of hydrogen sulfide that can be a principal cause of odor at a bioreactor. The odor problem may also be observed at the landfills where the sites' LFG collection system is inadequate to collect the higher rates of LFG generation. The first step in an odor control plan is to evaluate the need for additional LFG collection. Leachate sumps, riser pipes, cleanout pipes and similar access structures should be connected to the gas system to avoid fugitive emissions.

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

the aerobic landfill is very important. In the event that an explosive gas mixture is measured in any part of the system, the air injection system shall be stopped. The gas composition shall be measured again after two hours. If the composition remains in the explosive range, the gas extraction system shall be shut down and the gas be allowed to vent from the cap system. It shall be noted that the gas flare and blower system is designed with an explosivity meter designed to shut the entire system down if explosive mixtures are encountered in the system. If after two hours the gas composition is no longer in the explosive range, only a fraction of the injection wells (i.e. less air) will be brought on-line and gas mixture be checked again to determine if a leak or system short-circuit is the cause.

8.6.8 Bioreactor Closure:

Achieving waste stabilization is the ultimate goal of landfill bioreactor operations. Waste is stabilized completely when it no longer breaks down into byproducts that can be released into the environment. It is difficult to achieve complete stabilization and there are no indicators to suggest that the waste has been completely stabilized, but it is assumed to be stabilized to significant extent when the landfill leachate BOD/COD ratios are <0.1, the VOCs and metals trend downward and are reduced to below drinking water standards. This supports a stable nature of leachate from a degraded landfill and demonstrates that the source appears no longer to be a risk to human health and environment.

The other most appropriate indicator of the stabilization may be when over 95% of the gas has been produced and gas production rate has fallen below 5% of peak rates. In terms of solids, when the waste cellulose/lignin ratio is less than 0.2, waste biological methane potential is less than 0.045 m³/kg volatile solids added and dark and sludge like appearance of the waste may be another indicator (Reinhart and Townsend, 1997).

After the waste is stabilized, the moisture addition may be stopped and all the leachate collected from the bioreactor shall be treated before its disposal. And depending on the bioreactor closure plans, the waste may be mined for reuse and recycling, or may be used for other potential end use of the land.

It is expected that regulatory authorities may reduce the long term monitoring frequency and duration for bioreactors, recognizing the reduced potential for adverse environmental impact. Reduced liability and associated costs with minimal post closure monitoring will result in significant cost savings and will attract many operators to opt for bioreactor technology, the technology of the future.

Dissertations, Theses, and Projects:

Kim, H. (2005). "Comparative studies of aerobic and anaerobic landfills using simulated-landfill lysimeters." Ph.D. Dissertation. University of Florida, Gainesville, FL.

Townsend et al. (2008). "Bioreactor landfill operation, A guide for development, implementation, and monitoring" A report for the Florida bioreactor demonstration project (2008)

8.7 Summary and Conclusion

The Florida bioreactor demonstration project successfully utilized the data collected from the bioreactor research to develop standardized design and operating procedures. Several models were developed to simulate the parameter required for liquid introduction system and waste degradation for bioreactor landfills.

Jain et al. (2007) mathematically simulated data on some of the key variables that could be used to design vertical wells for liquids introduction at bioreactor landfills. The conclusions of this study were as follows:

- Hydraulic conductivity in the radial direction, moisture addition rate, and screen length of the well were found to have more significant impacts on pressure at the bottom of the well and the vertical extent of moisture movement than the anisotropy ratio.
- The anisotropy ratio was found to have a more significant impact on the lateral extent of moisture distribution than the flow rate, radial hydraulic conductivity, and screen length.
- Unsaturated flow properties (van Genuchten's parameters α , n) were found to have a minor impact on the parameters of interest of this study.
- From a design perspective, use of lower hydraulic conductivity, lower anisotropy ratio, and unsaturated media properties typical of sandy soil is advisable as a conservative approach for vertical well moisture addition systems when an estimate of these properties of waste at site is not available.

Gawande et al (2008) developed the model BIOKEMOD-3P, for **simulating solid waste biodegradation**. This model was able to simulate the experimental data of anaerobic biodegradation of solid waste in laboratory scale bioreactor. The model was also used to simulate simultaneous nitrification and denitrification processes in laboratory-scale microcosms. The model serves as a generalized numerical tool that employs use of an almost unlimited number of user-specified species and reactions. The model can prove to be a valuable tool for simulating data from a laboratory or pilot-scale bioreactor landfill to yield important kinetic parameters for process design.

The guide 'Bioreactor Landfill Operation: A Guide for Development, Implementation and Monitoring' was created and it compiles the practical experience learned from the Florida bioreactor demonstration project.

Attachment

BIOREACTOR LANDFILL OPERATION A Guide For Development, Implementation, and Monitoring