BIOREACTOR PERFORMANCE

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Disclaimer

Many site specific factors are needed for bioreactor landfill design. Values presented in this report are not presented nor should they be used for design purposes. Values presented in this report are only for demonstration purposes.

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Section 1
INTRODUCTION

The United States Environmental Protection Agency (EPA) and its predecessor agencies have been sponsoring various research and demonstration studies for bioreactor landfills since 1959. Most of the studies were completed in the 1970s and early 1980s. These studies showed that a landfill using leachate recirculation can be designed and operated to increase the rate of waste stabilization. In a bioreactor landfill, controlled quantities of liquid amendments are added and circulated through the landfill to achieve a desired waste moisture content. This process significantly increases the rate of biodegradation of the waste (similar to anaerobic composting), thereby reducing the waste stabilization period from 5 to 10 years instead of 30 or more years for a conventional "dry tomb" designed facility. The enhanced biodegradation also increases the short term production (but not total volume) of landfill gas, a mixture comprised predominantly of methane (CH_4) and carbon dioxide (CO_2). Methane can be recovered for electricity or other uses. The biodegradation and stability of waste also promotes settlement that increases the landfill capacity, delays the need for permitting new landfill operations, and reduces final cover maintenance during post-closure.

Most of these earlier studies have been included in prior literature reviews that focused on landfill stability or improvements in leachate quality to show the landfill can be used to store and treat leachate to environmentally acceptable levels. The studies also showed that by increasing gas production while operating, the amount of landfill gas remaining after closure will rapidly decline. These conditions were anticipated to shorten the likely post-closure care time frames for bioreactor landfills from 30 to 50 years to 5 to 10 years and thereby shorten the future potential liability to human health and the environment.

While general design and operational methods of adding and recirculating leachate and liquids were discussed in the previous studies, specific parameters affecting bioreactor performance were not evaluated. These include 1) leachate head on a liner, 2) side slope stability, 3) settlement, 4) leachate collection, 5) gas collection, and 6) prevention of fires.

This document is the summary paper that describes how leachate head maintenance, settlement, side slope stability, fire prevention, and gas collection were designed to protect human health and the environment at the five sites described in Section 4 and if any system enhancements were implemented after initial startup that improved operations.

Section 2
REGULATORY OVERVIEW

EPA promulgated Subtitle D of the Resource Conservation and Recovery Act (RCRA), Criteria for Municipal Solid Waste (MSW) Landfills (40 CFR Part 258; 56 FR 50978), on October 9, 1991. These criteria establish minimum performance standards for the siting, design, operation, and post-closure management of landfills that receive non-hazardous solid waste. EPA developed these regulations because landfills that receive non-hazardous solid waste have the potential to contaminate groundwater and create problems associated with gas migration. When developing Part 258 regulations, the EPA recognized the potential advantage of leachate recirculation and allowed recirculation of leachate at landfills that were constructed with a liner specified in the regulations (a composite liner consisting of 0.61 m of clay having hydraulic conductivity $\leq 10^{-7}$ cm/s overlain by a geomembrane) and a leachate collection and recovery system (LCRS).

Subtitle D of RCRA establishes minimum standards for landfill design and operation. Congress delegated the administration of Subtitle D to the States, which can develop more restrictive regulations. Some states (i.e., New York and Pennsylvania) require double composite liners.

Recently, three developments that have affected the permitting and operation of bioreactor landfills: (i) Project XL, (ii) the Research, Development, and Demonstration (RD&D) rule, and (iii) requirements for gas collection at bioreactor landfills. USEPA implemented Project XL to facilitate the use of superior technology quickly. Permits for innovative and superior technologies are to be processed rapidly with input from USEPA. To date, four bioreactor landfill projects are approved as part of Project XL. These projects should provide additional data on specific aspects of bioreactor landfills including issues related to the introduction of supplemental liquids to landfills and leachate recirculation in landfills with alternative liners.

EPA revised the Criteria for Municipal Solid Waste Landfills to allow States to issue research, development, and demonstration (RD&D) permits for new and existing MSW landfill units and lateral expansions. This rule allows Directors of approved state programs to provide a variance from certain MSW landfill criteria, provided that MSW landfill 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 MSW landfill permit. EPA finalized this alternative permit authority on March 22, 2004, and currently six states (Minnesota, Indiana, Illinois, Wisconsin, Michigan, and Missouri), have approved programs.

The RD&D rule adds flexibility to the existing 258 regulation to allow landfill owners to document that alternate approaches to design and operation of landfills may result in improved economics and/or environmental performance. The RD&D rule allows states to waive specific provisions of the MSW landfill criteria, including (i) operating criteria (except procedures for excluding hazardous waste and explosive gas control in Subpart C), (ii) design criteria in Subpart D, and (iii) final cover criteria in Section 258.6 (a) & (b). The rule allows alternate designs which might incorporate improvements in areas such as (i) liner system design and materials, (ii) leachate drainage and recirculation system design and materials, (iii) the addition of supplemental water to accelerate decomposition, and (iv) new liquid distribution techniques.

RD&D permits have an initial 3-year term, with three optional 3-year extensions, for a total of 12 years. The rule specifies that annual reports be submitted for all RD&D permits, and these annual reports summarize data obtained during the year and assess progress towards the goals of the specific RD&D permit at a site.

Specifically, related to bioreactor facilities, the rule provides that states can approve permits to allow the addition of non-hazardous liquids to a landfill unit constructed with an alternative liner (i.e., a liner that complies with the performance design criteria in 40 CFR 258.40(a)(1) rather than a liner that complies with the material requirements in 40 CFR 258.40(a)(2)). The State Director must be satisfied that a landfill operating under an RD&D permit will pose no additional risk to human health and the environment beyond that which would result from the current MSW landfill operating criteria. Under the RD&D rule permitting is still at the discretion of each state.

EPA issued a final rule on National Emissions Standards for Hazardous Air Pollutants (NESHAPS) for landfills in January 2003 (Federal Register, January 16, 2003, 40 CFR Part 63, National Emission Standards for Hazardous Air Pollutants: Municipal Solid Waste Landfills, EPA Final rule). Included in this rule are Maximum Achievable Control Technology (MACT) regulations that affect bioreactor landfills. In this rule, bioreactors are defined to include those landfills that add liquid, other than leachate and gas condensate, to reach a minimum average moisture content of at least 40% by weight to accelerate anaerobic biodegradation of the waste. Aerobic landfills are not included in this definition.

The rule requires that landfill gas collection and control systems begin operation within 180 days after initiating liquids addition, or within 180 days after the landfill moisture content reaches 40% by weight, whichever is later. This rule applies only to bioreactor cells that receive liquids other than leachate and that have a design capacity greater than 2.5×10^6 Mg or 2.5×10^6 m^3. Affected sites are required to submit startup, shutdown, and malfunction plans, and to track and report every six months any deviations from air pollution limits.

In summary, the operation of landfills with leachate recirculation has always been allowed under Part 258, but addition of liquids other than leachate and gas condensate has not been allowed. The addition of such liquids could be permissible under the RD&D rule or through Project XL. In all cases, whether a traditional Part 258 permit, a Project XL application, or an application under the RD&D rule, the ultimate authority to permit the construction and operation of landfills will rest with the states. The approach of the states has varied considerably, although many states have become more receptive to the operation of landfills as bioreactors. [1]

[1] *State-of-the Practice Review of Bioreactor Landfills*; Craig Benson, Morton Barlaz, Dale Lane and James Rawe, for USEPA; April 6, 2005.

Section 3
SITE SELECTION OVERVIEW

The five sites that were selected for inclusion in this summary paper are as follows:

- Site 1 – Crow Wing County Landfill, Minnesota
- Site 2 – Williamson County Landfill, Tennessee
- Site 3 – Burlington County Landfill, New Jersey
- Site 4 – New River Regional Landfill, Florida
- Site 5 – Salem County Landfill, New Jersey

EPA selected the sites from a preliminary list of nine facilities whose locations had quality data sets, high liquid addition rates and were a mix of aerobic and anaerobic design.

A brief summary of the information pertinent to each site as a bioreactor facility is presented below.

Crow Wing County Landfill

- Location: North Central Minnesota
- Owner: Crow Wing County
- Annual tonnage: 50,000
- Permit method: Leachate recirculation demonstration to current MSW landfill permit
- Extent and area: Full scale; 14.1 acres
- Type: Leachate recirculation; anaerobic
- Year started: 1998
- Method of injection: Treated and untreated leachate are injected via horizontal laterals, working face spray; spray on yard waste composting over intermediate cover
- Annual volume recirculated: 4 million gallons

Williamson County Landfill

This bioreactor is the only full aerobic bioreactor of the five sites selected.

- Location: Central Tennessee, Williamson County
- Owner: Williamson County
- Annual tonnage: About 70,000 tons disposed in closed landfill on approximately 7 acres
- Permit method: State permit for leachate recirculation
- Extent and area: Full scale in 7 acre closed landfill
- Type: Leachate and stormwater recirculation; aerobic
- Year started: June 2000
- Method of injection: Leachate and air are injected into vertical risers with force main and header from storage tank that were retro-fitted for the closed landfill
- Annual volume recirculated: About 1 million gallons

Burlington County Bioreactor

- Location: Northwest New Jersey
- Owner: Burlington County
- Tonnage in-place: About one million tons of MSW in a 10 acre area
- Permit method: NJDEP permit for leachate recirculation including leachate from closed landfill (pre-subtitle D), stormwater runoff from co-compost area, stormwater ponds, grey water and sewage from office and lab complex, and surface water
- Extent: Full scale leachate and liquid recirculation installed as landfill was being built
- Type: Anaerobic recirculation from 2002 to 2005
- Method of injection: Leachate recirculated into horizontal pipes and trenches with force main connection to storage tank
- Volume recirculated: About 18 million gallons to date

New River Regional Bioreactor

This bioreactor is the only "research" bioreactor designed, operated, and permitted with State of Florida grant funding made available through the "William W. "Bill" Hinkley Center for Solid and Hazardous Waste Management" Gainseville, Florida.

- Location: North Central Florida
- Owner: Union County
- Tonnage in-place: About one million tons in an existing filled 10 acre area
- Permit method: FDEP permit for leachate recirculation
- Extent: Full scale leachate recirculation into an existing interim capped landfill with an exposed membrane cover

- Type: Anaerobic bioreactor in 75 % of site and aerobic bioreactor in 25% of landfill boundary
- Method of injection: Air and leachate injected in nested vertical risers
- Volume recirculated: About 6.5 million gallons injected to date

Salem County Bioreactor

- Location: Southwest New Jersey
- Owner: Salem County
- Permit method: NJDEP permit for leachate recirculation
- Extent and area: Full scale leachate recirculation as landfill was constructed; over 5 acre area
- Type: Anaerobic bioreactor with leachate recirculation since 2000 and MSW moisture added to date is about 44 gallons/ton
- Method of injection: Leachate recirculated from storage tank and force main to subsurface horizontal injection trenches

Section 4
DESIGN INTENT AND PERFORMANCE

4.1 Liner Head Maintenance

Part 258 requirements state that leachate head on the liner cannot exceed 30-cm under normal operating conditions, and reintroduction of leachate into a waste mass in quantities that are near field capacity increases the possibility of exceeding the head depth on the base liner system. Each facility addressed this requirement with a leachate collection design as described below.

4.1.1 Crow Wing County Landfill

The leachate collection system at the Crow Wing County (CWC) Landfill consists of perforated lateral pipes at the base of Cells 1 and 2 that penetrate the liner and convey flows via gravity directly into a pump station. A collection lateral in the base of Cell 3 drains to an internal sump where the leachate is pumped into a gravity line that empties into the same pump station. All three cells have the standard Part 258 design with two feet of compacted clay overlain by a 60 mil HDPE geomembrane and 18 inches of drainage sand with hydraulic conductivity greater than 10^{-3} cm/s. Collection laterals are surrounded by 1.5 inch stone wrapped in filter geotextile.

As with Part 258, Minnesota solid waste rules for municipal solid waste landfills require that leachate head on top of the liner not exceed 30 cm (~1ft). Leachate head must be measured on the landfill base at a minimum weekly with exceedances reported to the regulatory agency. At the CWC Landfill, two methods are used to measure leachate head:

1. In Cells 1 and 2, a side slope head well, fitted with a transducer, was installed at the low elevation of the two cells.
2. In Cell 3, the internal sump pump is fitted with a transducer.

Both transducers activate a strobe light if the leachate elevation exceeds the elevation representing one foot above the liner at the transducer location.

Since recirculation began in 1998, one foot of leachate head has not been exceeded in any of the three cells.

4.1.2 Williamson County Landfill

A review of the leachate recirculation field data for this bioreactor shows the average daily injection rate from June 2000 to February 2005 has approximately been 14,000 liters per day of leachate (370 gal. per day), with an average daily leachate injection rate of 114 liters per day per meter of screen length (9 gal per day per foot). Leachate injections occured at various times of the day as the float switches in the mixing tank are activated based on inflow leachate production (i.e., it is not a steady rate of injection over 24 hours, but is dosed at various times of the day).

The liquid sources for the site are primarily leachate, precipitation (i.e., infiltration after runoff and evapotranspiration effects), and periodic storm water injection. Direct injection of liquids occurs on-site via vertical injection wells. The wells are 2.5 and 5 cm (1 and 2 inches) diameter vertical PVC wells. The 2.5-cm wells are screened from approximately 0.9 to 1.5 meters (3 to 5 ft) from the surface to the bottom of the well. The 5-cm diameter wells have been installed in cluster arrangements with screened lengths at various discrete depths within the waste (due to stratified layering of waste and soil zones).

Liquids (consisting almost exclusively of leachate) were applied throughout the day at periodic times depending on the liquid level in the 7600-liter mix (equalization) tank located on top of the landfill bioreactor. The submersible sump in this tank operates off a float-switch controls based on pre-designated "on" and "off" liquid levels in the tank. The peak value of injection occurred during the fall of 2000 while attempting to increase moisture content before activating the blowers. Approximately 30% of the total volume injected has emerged as leachate.

The leachate collection system at the landfill bioreactor cell consists of a 30-cm crushed stone drainage layer. There are no collection pipes within the leachate collection system (LCS) of the landfill bioreactor. The base of the landfill bioreactor cell is sloped at approximately 2% toward the southeast corner of the footprint. All of the leachate drains into a collection manhole located in the southeast corner of the cell. The manhole is perforated along the upslope side of the manhole to facilitate leachate drainage into the structure. Originally, leachate collected from this cell was mixed with leachate from other areas of the landfill and hauled to an off-site wastewater treatment plant in Fairview, Tennessee. However, since the initiation of the landfill bioreactor research, all of the leachate collected from the entire landfill site is being collected at this bioreactor cell manhole and is injected into the landfill bioreactor. Leachate collected from within the landfill bioreactor LCS at the base collection manhole is recirculated back into the landfill bioreactor waste mass. Since the start-up of the landfill bioreactor system in June 2000, there have been no shipments of leachate for off-site treatment.

Leachate head is monitored via four riser pipe locations. The base of the risers extends into the waste fill, with the pipe invert located at the top of the liner system. The slope risers are "L-shaped" units constructed of PVC pipe and consist of a horizontal leg installed directly on top of the liner geomembrane and a vertical section that protrudes out of the sideslope for access by field personnel. The top of the vertical riser section was originally surveyed for top-of-casing elevation.

To date, the maximum head over the liner system based on these measurements has been 10 centimeters. The head over the liner measurements at the four riser pipe locations have remained relatively steady.

4.1.3 Burlington County Landfill

At the Burlington County Resource Recovery Complex in Mansfield and Florence Townships, NJ, head is monitored using piezometers in the sand drainage layer on the floor of the landfill. Leachate is injected in horizontal perforated pipes. About 68 million liters (18 million gallons) were injected in the first 1.5 years of operation in the approximately 4 Hectare (10 acre) bioreactor landfill cell. The estimated moisture content of the MSW is estimated to have been increased up to 45 percent by wet weight.

The initial transducers used in the piezometers gave erroneous readings. The range of the selected transducer was not appropriate for monitoring a 30-cm maximum range. The original transducers selected did not have the resolution to monitor the 0-30 cm range accurately. New transducers were installed and correlated against readings at the leachate collection sumps, verifying head on the liner has been maintained less than 30 cm (1 ft).

4.1.4 New River Regional Landfill

The New River Regional Landfill Bioreactor consists of two contiguous landfill units, cell 1 and cell 2. The leachate collection system of both these units is a standard Part 258 saw-tooth leachate collection design, with HDPE drainage pipes placed in trenches at parallel locations throughout the landfill. Each of these collection pipes drains through penetrations in the liner to independent manholes. The leachate in all the manholes is gravity drained through a common pipe to a master pump station where it is then pumped to the leachate management lagoons.

Liquid addition rates are dictated by HELP model runs predicting head on the liner as a result of liquid injection rates. A constraint on the injection rate was based on the amount of liquid collected from each individual line. If flow rate from a particular collection line was greater than the amount estimated by the HELP model, it would indicate a head on the liner that is greater than 30 cm (1ft). If that occurred, leachate recirculation would be discontinued. To date, over 6.3 million gallons of leachate have been recirculated at the site.

4.1.5 Salem County Landfill

The leachate collection system consists of an eight inch diameter perforated collection pipe on top of the liner with stone and fabric wrapped around the pipe. The surrounding leachate drainage media is sand. Leachate is gravity fed to a sump with two five-horse power pumps. Leachate is pumped to a 760,000 liters (200,000 gallons) storage tank onsite. All leachate is metered daily.

Leachate recirculation commenced in 2000. Currently the total amount of leachate injected per ton of MSW is approximately 170 liters (44 gallons). Leachate is recirculated in twelve injection systems consisting of horizontally placed six inch HDPE perforated lines placed in the landfill at a depth of 24 meters (80 ft) above the liner. The first 30 meters (100 ft) of each injection line pipe is not perforated. The injection pipes are joined at sets of two headers with valves for each line allowing single or multiple injections at the same time. Leachate head is measured at the sump. There have been no apparent increases over 30 cm (1 ft) of head above the liner. Calculations using a water balance show that approximately 2,000 gallons per acre per day of leachate can be re-injected into the landfill without exceeding one foot of head on the liner.

4.2 Settlement

Settlement, while not the sole indicator of waste stabilization, may signify that the waste is decomposing, and the amount of settlement can be directly related to the amount of liquids introduced into the waste mass.

4.2.1 Crow Wing County Landfill

Airspace at CWC has historically been monitored using airspace utilization factor (AUF) calculations. Cell 1 was constructed in 1991, and recirculation began in 1998. Accordingly, the pre- and post-recirculation AUF is 1,004 pounds per cubic yard and 1,341 pounds per cubic yard, respectively. AUF should increase in future years as recirculation continues and Cell 3 waste is compacted with the placement of additional lifts.

In addition, the County installed four settlement plates in 2000 and 2001 at the waste level of two of the horizontal laterals. Data indicate that over 20 percent settlement in waste height has been realized within five years.

Piping flexibility has been included in the system design. Recirculation laterals are constructed with alternating four-inch and five-inch diameter length, with a five foot engagement at each end to allow the lateral to stretch with waste settlement. Recirculation lateral connection to the forcemain is made with a flexible stainless steel connection. The four original laterals installed in 1998 are still open and operable after nine years.

4.2.2 Williamson County Landfill

Monthly topographic surveys of the bioreactor surface are carried out to detect settlement across the site. An initial survey of the landfill bioreactor surface occurred in January 2000, several months prior to the start-up of the landfill bioreactor operation in June 2001. This established a baseline surface for future comparative assessments. Dedicated settling pins (e.g., settlement plates) were positioned along the plateau. Each pin is a 45-cm section of re-bar with a plastic cap attached to one end of the bar. The re-bar was placed into the top of the landfill bioreactor surface to the point where the capped end was facing up and flush with the original ground surface. The 45-cm length were chosen in order to limit the effects of bar movement due to frost heave.

Results of settlement as of April 2005 show a 0.53-meter to 1.2-meter drop in the surface elevations since the landfill bioreactor operation began. The comparisons of the April 2005 elevations with the original survey in January 2000 show a 5.1% to 10.7% decrease in waste height over a 59-month period of operation. The mean settlement percentage relative to waste depth is 7.8%.

The settlement that has occurred at the bioreactor has not resulted in any infrastructure damage. The injection pipe and well system has been equipped with flexible tubing connections that accommodate movement. The leachate injection tank was strategically located over an area of the bioreactor top where limited waste had been placed and where minimal settlement was anticipated. There has been no damage to the tank or its foundation as of this date.

4.2.3 Burlington County Landfill

The Burlington County Landfill bioreactor measures quarterly settlement surveys with settlement plates and annual air photography surveys for topographic comparisons. They observed substantial settlement over the last 4 years of operation increasing the effective density of MSW from 500 kg/ton (1,120 lbs/ton) to over 720 kg/ton (1,600 lbs/ton). Some infrastructure issues have been observed with settlement due to the horizontal leachate injection pipes going inward into the landfill which strained the leachate distribution header force main system and caused a bend and kink in the pipe. This was due to not enough "slack" placed into the connection with the laterals and the header. Gas wells that were installed as vertical wells also have been observed to have a "kink" deeper in the landfill as seen in video analyses. This was due to high temperatures of 160 degrees F (due to rigorous degradation of MSW at increased depths) which tends to deform PVC pipe. The vertical wells are being replaced with CPVC which has better structural integrity with higher temperatures.

4.2.4 New River Regional Landfill

The New River Regional Landfill bioreactor used nested vertical wells that are 6, 12 and 18 meters (20, 40, and 60 ft) deep from the landfill surface and are used to inject 25 million litters (6.5 million gallons) of leachate. The settlement was measured with GPS coordinates on the landfill surface and with settlement of each nested vertical injection well. The settlement data were plotted in feet of settlement over time in days. Measured settlement was the greatest at the shallow injection wells and the least at the deepest injection well. The depth of settlement was the greatest at the injection well and declined with radial distance from the well up to 15 meters (50 ft) away and then leveled off. The data also showed a distinct relationship with total settlement and the amount of moisture added in gallons. A direct linear relationship appeared to exist (i.e., the greater the total amount of leachate recirculated, the greater the settlement).

Settlement of the landfill has not caused any integrity problems. The New River Regional Landfill is a "retro-fit" bioreactor and has an exposed geomembrane cover with numerous vertical injection well points and instrumentation through the cap. There has been no disruption to the cap integrity or the vertical and horizontal gas wells. Leachate risers and systems also appear to be functioning adequately. Settlement appears to be very manageable at this bioreactor landfill.

4.2.5 Salem County Landfill

Settlement has been observed at a rate of about 1.5 meters (5 ft) per year greater than the previous observed settlement before leachate recirculation commenced. Due to the flexible properties of HDPE pipe for injection systems and gas headers as well as the design and installation that allowed for settlement, there has been no damage to the landfill infrastructure to date.

4.3 Sideslope Stability

4.3.1 Crow Wing County Landfill

The Crow Wing County Landfill has been developed with 4:1 final slopes and 3:1 internal intermediate slopes. Recirculation laterals are solid within the outside 15 meters (50 ft) of outboard slopes. Lateral loading during operation has been conducted within design limits. During design, veneer and circular slope stability were evaluated with safety factors above 1.5 maintained. No other design, operation, or monitoring controls have been used to address slope stability. Although considerable settlement has been observed subsequent to recirculation, this movement has not created slope stability concerns. The sandy cover soils used for intermediate cover promote liquids movement and minimize potential for pore pressure build up.

4.3.2 Williamson County Landfill

Routine manual inspections at the sideslopes were carried out to detect leachate seep locations. If seeps were located, the valve at the leachate injection well located nearest the seep location was throttled back. There were no original structural controls installed for slope stability at the Williamson County site. Sideslope riser pipes were installed prior to the start-up of the landfill bioreactor as slope inclinometer monitoring units. These four pipe units are located along the south and east sideslopes for the landfill bioreactor. The east and south slopes are the steepest slopes associated with the cell (1.5:1 horizontal-to-vertical) and county personnel and the site engineers considered monitoring the potential movement of these slopes essential. In addition, the horizontal coordinates (x,y) were surveyed. The x,y,z coordinates provided the baseline reference for future monitoring of potential slope movement. These units were placed in a manner to attempt to detect potential global slope failures that may occur along the geomembrane liner surface and the overlying soil/waste mixture. The x,y,z coordinates for the top-of-casing for each of these slope inclinometer units are surveyed, recorded, and evaluated every month to attempt to detect any significant movement in these pipes.

Two veneer failures have occurred during the operation of the landfill bioreactor. The first occurred on February 27, 2001. This failure involved only the mulch and upper soil cover layer. The cause of this failure was due to blocked storm water drainage on the top deck of the landfill that saturated the soil cover materials. Placement of the mulch appears to have restricted storm water movement so that storm water pooled in a low spot near the crest of the eastern slope. This failure was not a result of bioreactor design.

The second failure occurred on May 4, 2002. The cause of this slide appears to be due to excessive moisture flow that moved along the surface of an interior soil intermediate cover layer, exiting as a breakout mid-way up the south sideslope. This saturation of the middle slope area appears to have weakened this area of the slope resulting in a veneer shift of the surface. It is also theorized that the excess gauge pressure from the pressurized air injected into the mass from the blowers contributed to this failure. This failure may have been the result of the bioreactor operation but has since been corrected by lowering leachate and air injection pressures in this area. Both failures occurred within the soil and mulch cover layer and did not involve failure within the waste material or the slope of the waste.

As a result of the failures, moisture injection at the very top perimeter of the south and east slopes, immediately above the top of each slope, was suspended. A rock buttress was constructed along the south slope; these buttress units were constructed of a sand underdrain layer and rock overlay portion to provide a counterbalance weight to prevent further slope displacement. The buttress also provides a sufficient high porosity layer to help dissipate pore pressures along the slope. The south slope buttress was essential because the blowers and the data collection trailer for the landfill bioreactor system are both located at the base of the south slope.

4.3.3 Burlington County Landfill

Burlington County's side slopes are constructed at 3.5 (H) to 1 (V) for permanent slopes and 3 (H) to 1 (V) for internal, temporary slopes. To date only one area with any kind of a stability problem has been observed, a 61 by 4.6 meters (200 by 15 ft) area along the 3.5:1 slope where the 30 cm (12-inch) thick intermediate cover was saturated and developed a 10 to 30 cm (4 to 12-inch) wide crevice. A field investigation confirmed that the crevice did not extend through the cover material into the MSW fill. Standard survey methods are used to establish fill slopes. Whenever the County observes seeps (leachate trickling down the slope as opposed to wet areas on the surface of the slopes) along the permanent slopes, the rate of recirculation in the affected areas is reduced.

A toe drain also was retro-actively installed and intercepts leachate and gas from the side slope area. During the excavation of this toe drain substantially degraded MSW were encountered showing the rapid stabilization of waste that has occurred with this bioreactor. Also, leachate injection lines were installed only 8 meters (25 ft) of solid pipe from the side slope and this may have caused leachate seeps. As a result, the injection rate of leachate dosing was reduced. The next cell will have leachate recirculation lines set back further from the side slope with solid pipe to avoid the operational issues in the first bioreactor cell. A temporary 20 mil tarp also was placed on the outward slopes and intercept leachate seeps to a toe drain.

4.3.4 New River Regional Landfill

The operator of the New River Regional Landfill bioreactor has monitored the stability of side slopes and has not had a problem with waste movement or infrastructure. Part of the design of the side slope of the landfill incorporated horizontal gas collection pipes. The design of the injection systems also helped prevent side slope instability. Injection systems were installed no closer than 30 meters (100 ft) from the side slope. A leachate toe drain was installed at the base of the side slopes to intercept any leachate seeps. Leachate pore pressure was monitored with piezometers. The landfill also was monitored with numerous down hole instruments that detected the area distribution of moisture. Excess moisture would have been noted in the periphery of the landfill.

4.3.5 Salem County Landfill

Since the leachate injection systems have been designed to have solid pipe for the first 30 meters (100 ft) from the side slopes, there have been no problems with slope integrity or unusual movement. Slopes are designed to be built initially with a 3:1 slope and 30 cm (1 ft) of clay as interim cover to prevent leachate seeps. Also, perennial grass seed and a mixture of crown vetch has helped to stabilize the side slopes.

There were minor leachate seeps when the leachate recirculation system was first operated, but the leachate re-injection rates were reduced by half. This avoided seeps since the reduced rates were established along with the interim cover.

4.4 Fire Prevention

4.4.1 Crow Wing County Landfill

No specific design, operation, or monitoring methods were implemented in this project related to fire prevention. No fires have been reported.

4.4.2 Williamson County Landfill

Temperatures have been used as a feedback parameter for the operation of the bioreactor system in order to determine if additional liquids are needed to lower excessive temperatures. Temperature monitoring via the thermocouple system was a very successful operation. There were no indications of any underground fires and very isolated and infrequent high temperature spikes. Only one area reached temperatures near the allowable operating threshold of 70 degrees C. Additional leachate was injected into the “hot” area in an effort to control the temperature. The method appeared to work well for several days. However, the temperature began a steady increase thereafter. On May 3, 2002, the blowers were shut down in response to slope stability issues. After 20 hours, the “hot spot” had dropped over 8 degrees C. There have been no other issues with excessive temperatures as of this date. Underground fires are prevented by mitigating “hot” areas through the introduction of excess moisture or reduction of air flow to the affected area. This shows that the system can be designed to operate under threshold temperatures where air is automatically decreased and leachate injection increased when temperatures are exceeded.

4.4.3 Burlington County Landfill

The Burlington County Landfill bioreactor has observed high temperatures in MSW up to 71C (160F) in vertical gas wells. A "hot spot" was also observed when CO was monitored. The CO levels and temperature declined substantially when additional leachate was recirculated in this area of the landfill. The porous interim cover (mostly sand and recycled glass), coupled with excess LFG collection system vacuum, resulting in air intrusion was believed to have caused this problem. Careful tuning of the gas field with laterals and vertical collection has ensured that there is a balance of the system and fires have since not been observed.

4.4.4 New River Regional Landfill

The New River Regional Landfill bioreactor operates both an anaerobic and aerobic system that are adjacent to each other. There has not been an increased temperature issue in the anaerobic section of the landfill to warrant fire concerns. This in part most likely is due to the efficient gas collection system that was installed under the geomembrane cap. This along with proper gas vent balancing, prevents air intrusion that has the potential to cause a fire, in particular when methane concentrations reach a range between 5 to 15 percent. Temperature sensors also were installed at depth in the bioreactor. Temperatures have never exceeded 55 C whereas a threshold temperature of 78 C was regarded as the highest not-to-exceed due to the potential to start thermophylic reactions. Leachate injection also helps keep the landfill cooler if it heats up unexpectedly.

The data for the aerobic leachate side of the landfill consisted of temperature profiles at various depths with a maximum temperature of 78 C as a not to exceed goal. The potential for fires is somewhat greater at an aerobic landfill, especially at a "retro-fit" bioreactor that already is anaerobic and is generating landfill gas with 55% methane. The increased temperature created by aerobic waste decomposition can promote spontaneous combustion if not controlled. The facility had developed two different methods for leachate injection. The first method used an air injection/leachate recirculation schedule. After air was injected, the shallowest monitoring sensor of temperature approached the threshold temperature after 15 days of air injection. The conclusion was that not enough leachate was added and too much time elapsed between recirculation and air injection. Once air injection was stopped, temperature declined.

The second injection scenario recirculated substantial quantities of leachate above the vertical injection zone where air was added. This greatly helped to moderate temperature fluctuation.

4.4.5 Salem County Landfill

Landfill fires have not been observed. Control and monitoring of the gas collection system ensures that limits on vacuum do not pull too much oxygen or outside air into the landfill.

4.5 Gas Collection

4.5.1 Crow Wing County Landfill

Currently landfill gas is passively vented at CWC, and concentrations of methane have been as high as 60%. Vent wells installed for the passive system are convertible to active well and were constructed of CPVC to withstand higher bioreactor temperatures. An active collection system is proposed as part of the Recirculation-to-Energy (RTE) project that will reclaim and reuse the generated landfill gas. Modeled collectible landfill gas approaches 11 m^3/min (400 cfm) over the 14 acre fill area that has less than 1 million cubic yards of waste in place. The system would be designed to accommodate early gas generation and moisture control. The RTE concept promotes landfill gas to energy projects at non-NSPS landfills due to the accelerated LFG generation resulting from liquids recirculation.

4.5.2 Williamson County Landfill

There is no active or passive gas collection system installed at this bioreactor. The original assumption was that the air injection (i.e., aerobic bioreactor) would keep methane gas concentrations low enough to rule out the need for an active collection system. Based on the gas measurement data obtained from the monitoring wells at the bioreactor, this assumption has not been validated. Only a maximum of two blowers can run simultaneously because of the excessive air pressures within the piping system and the inherent physical limitations on the system (e.g., hose rupturing, pipe leaks). During times when the PVC-header system for air is secure, with no air leaks, evidence of good air distribution between injection wells was established. During these times, the percentage of methane gas measured at the site decreased and internal temperatures rose. However, during those times, the header backpressure would go up. The side slope risers also were used for head measurements and were routinely measured for landfill gas in order to assess gas mixtures near the base of the landfill. These pipes are positioned to capture gas from the lowermost layers of the bioreactor waste.

In 2002, tests were performed at the landfill to assess the influence of air injection on the monitoring wells stationed across the site. The monitoring wells are positioned anywhere from 9 to 15 meters from the nearest injection well. It is possible that, with the right hardware and equipment, significant air distribution within the retrofit landfill waste mass is possible and does influence gas mixtures and, ultimately, the redox conditions within the waste mass.

It is interesting to note, as part of the gas emissions monitoring work at the bioreactor, carbon monoxide was detected in a small number of wells during the initial air-injection phase of the blower operation, which was sporadic in late 2000 and was permanently activated in 2001. There were no indications of any landfill fires within the bioreactor at any time during this period. It is unknown at this time, as to the source of the carbon monoxide. There is limited gas data from the site before the bioreactor became operational; however, the limited gas data that exist indicate non-detects for carbon monoxide before the blowers were turned on.

4.5.3 Burlington County Landfill

The Burlington County Landfill bioreactor incorporated active gas collection into the 10 acre cell as it was being constructed. Horizontal gas collection systems were installed 3 feet above the leachate collection laterals at locations in between the leachate injection systems. These were effective in collecting gas until the landfill reached substantial moisture increases due to leachate recirculation. Many of the horizontal gas collectors were saturated and vertical wells were installed. The next cell will have further vertical distance between lower leachate recirculation laterals. In drilling the vertical gas wells, substantially degraded MSW was encountered at the elevation of the horizontal gas and leachate recirculation lines. Very little gas was yielded in this area. However, due to localized areas of perched saturation, air-driven pumps were installed in the vertical gas wells. Substantial fluid flow is being removed resulting in better gas yields per well. When the temporary 20 mil tarp is installed, it is expected to greatly improve odor control and gas collection efficiencies, trapping odor and surface gas emissions under the tarp.

4.5.4 New River Regional Landfill

The aerobic section of this bioreactor does not have the need to collect methane gas as it is being oxidized by injection of air. The landfill gas collection system in the anaerobic section, however, is highly efficient due to the interim geosynthetic cover system and the combination of vertical and horizontal well installation. Horizontal wells were installed near the top of the landfill. Due to leachate injection, dewatering pumps were installed in the vertical wells to optimize gas collection. It was found that leachate that is reinjected also tends to migrate towards gas wells with the vacuum. Horizontal wells also were continued down the side slopes. Leachate sumps and clean-out risers also were connected with a vacuum and this combination of gas collection covered the top, bottom and sides of the landfill. Leachate recirculation systems also can be hooked up to a vacuum when not in use and need to be rotated to give time for leachate to drain out of the system. After time, however, extracting gas out of leachate recirculation systems causes saturated conditions around the injection areas from migration of liquids through short-circuiting.

After data were collected on the volume of gas from each of these areas, it was discovered that 10 % of gas generated was from manholes, 28 % was from the top surface of the bioreactor and about 62% was generated from the side slopes of the bioreactor. This shows the importance of collection from side slopes and controlling pore pressure in side slopes for stability as well.

4.5.5 Salem County Landfill

Although the Salem County Landfill bioreactor is below the capacity threshold that would cause it to be regulated by NSPS rules, they have installed an active gas collection system that was originally set up as a passive flare system. Soon after leachate recirculation commenced, the facility increased gas control from 2 to 10 candlestick flares. Since then, a utility flare and blowers were installed for more efficient gas collection. Gas control efficiency is estimated at over 90 percent. This is due to the installation of horizontal gas collection piping located about 15 to 18 feet above the recirculation pipes as the landfill was being built. The benefit of the bioreactor in increasing gas production may be realized at this site as it is estimated that nearly 1 MW of power could be generated.

Section 5
KEY FINDINGS

The purpose of this report is to evaluate specific parameters affecting bioreactor performance, including 1) leachate head on a liner, 2) settlement, 3) side slope stability, 4) fire prevention, and 5) gas collection. The previous sections evaluated each of these parameters related to protecting human health and the environment at the five sites described therein. Key findings are presented below.

5.1 Liner Head Maintenance

The landfill that has measured the highest leachate recirculation rate (loading rate) was Crow Wing County. About 75 gallons of leachate per ton of MSW were recirculated in 2005. There have been no problems noted in maintaining less than or equal to 30 cm of head of leachate on the primary liner. CWCL also is the only landfill of the five evaluated that has lysimeters (leak detection system) below the primary liner and leachate sump. The flow in the leak detection system is below levels of concern and has not correlated with the rates of leachate recirculation or leachate generation and/or rainfall over the history of the landfill.

The other four bioreactor landfills had no historical problems in maintaining less than 30 cm of head of leachate on the liner. Williamson County Landfill and New River Regional Landfill reported historically low leachate head (10 cm or less) during the bioreactor operations. NRRL also is the only bioreactor of the five evaluated that was able to maintain low heads with a “pipe-less” collection system design using only triplanar geocomposite for the drainage media with gravity flow to a collection sump. There also was no apparent correlation of leachate recirculation rates, leachate generation rates and liner head maintenance in any of the five bioreactors reviewed. This most likely is due to good moisture distribution of the leachate recirculation system designs and operations that evenly dispersed leachate laterally and vertically into the waste mass to the point of absorption (i.e., less than field capacity).

As was demonstrated at each site, with each having a different leachate collection approach, the engineered systems are all functioning as intended to maintain head less than one foot over the liner.

5.2 Settlement

A common variable between all five of the bioreactor landfills has been the use and recommendation of HDPE pipe (solid and perforated) that is flexible enough to handle settlement. Experience at Williamson County Landfill bioreactor has shown that the type of piping material selected is important to the delivery of air and fluids. At first, PVC header pipe and joint connections were used. This was found to be brittle after exposure to sun and also was subject to settlement and cracking. As a result, air leaks were found (which was important since this was an aerobic bioreactor). After piping was replaced with HDPE, there have been no problems with integrity even with additional settlement of the landfill.

Only Burlington County Landfill bioreactor reported initial problems with infrastructure and settlement. They observed that the lateral injection and gas collection system piping were pulled inward to the landfill slope with settlement, causing the header pipe connection to crimp or kink. This problem later was corrected by replacement of new pipe with adequate "slack" within it, especially at connection of header and lateral piping.

The NRRL also allowed for settlement in their design and installation and did not observe any structural damage to infrastructure. Salem County Landfill bioreactor also used and recommended HDPE pipe with extra slack to allow for settlement and has not noted any infrastructure problems due to settlement. Crow Wing County Landfill bioreactor used a unique design of 4" pipe placed in an overlapping 5" pipe with a Furnco coupling. This allowed sufficient flexibility in the joint and slack for settlement. No problems with leachate injection systems have been observed since the leachate recirculation started in 1998.

5.3 Sideslope Stability

The only landfill that witnessed side slope issues was Williamson County aerobic bioreactor. This facility had two minor veneer failures, most likely due to its steep side slope of 1.5:1. The first failure was in a small area and was only the compost cover slumping due to heavy rainfall and run-off. There was no failure noted in the waste mass within the landfill or due to bioreactor operations. The second failure was due to excess pressure noted in one well which may have been created by air and leachate injection. Leachate seeps midway up the slope appeared to have been the cause of this veneer slumpage. When the cover was replaced, there were no further incidents as leachate and air quantities were lowered for injection back into this section of the landfill.

Burlington County Landfill had leachate seeps most likely due to gas wells that were watered out and leachate recirculation lines that were perforated within 7.6 m (25 ft) of the side slope. This was corrected and has never occurred since then as gas wells were equipped with dewatering pumps and leachate recirculation was terminated in this section of the landfill. None of the other landfills had side slope issues or instability.

It appears that bioreactors that design and operate with the prevention of potential leachate seeps in side slopes do not experience slope instability. A functioning leachate injection line from 15 to 30 meters (50 to 100 ft) from the edge of the outside slope should ensure that pore pressures will not build up to affect slopes. Also, the use of alternate and permeable daily cover will help avoid seeps and instability.

5.4 Fire Prevention

Two of the five landfills reported experiencing conditions which posed the potential for "fires". Williamson County Landfill bioreactor had a "hot spot" over their temperature goal which was quickly remedied by adding more leachate and reducing air injection. No hot spots occurred again as monitoring and liquid management controlled temperatures.

Burlington County Landfill bioreactor had a "hot spot" that appeared to be a subsurface fire, but was readily controlled by reducing vacuum on the gas wells and balancing the system. The condition was caused by too much air withdrawn through the thin interim permeable cover. It was controlled by addition of extra leachate injected in the area.

It appears that fire prevention and occurrence is similar in frequency to "dry tomb" landfills and is a matter of gas tuning, balancing and monitoring. Excessive air intrusion and dryness of MSW contribute to fires in any landfill. Aerobic bioreactor landfills may be most vulnerable, but it is a matter of monitoring and control of liquid addition. NRRL also found that in aerobic landfills the simultaneous addition of liquids and reduction in air injection volume will help control temperatures in a desirable operating range.

5.5 Gas Collection

There were no gas collection systems necessary for the non-aerobic landfills that included Williamson County Landfill and the aerobic portion of NRRL. Methane that existed in both of these "retro-fit" landfills were oxidized within a day or two of operation and did not pose a threat to the environment as there were no gas migration issues. Also, due to its size, Crow Wing County Landfill did not install active gas systems as it is passively vented. Plans are to install an active system within the next year and sell landfill gas for energy.

The other anaerobic bioreactors that had installed gas collection systems designed and installed them during construction of the leachate injection systems. Both horizontal and vertical gas collection systems were installed and operated. A common theme was to install dewatering pumps and also to locate gas extraction systems well away from active leachate injection systems. Also, some landfills did not operate gas collection in areas of active leachate injection. Most sites also rotated the injection of leachate around the site so as to not over saturate any one area and to allow time for leachate to drain. This should also provide relief to gas collection systems.

Burlington County Landfill bioreactor also discovered that if vertical gas wells are installed deep within the zone of active biodegradation, then the temperatures in the waste are such that PVC pipe will weaken. There were a few vertical gas wells that were "crimped" at depth. They will be replaced with CPVC that has a higher melting (or weakening) point.

5.6 GENERAL CONCLUSIONS

A review of the literature and evaluation of five selected full scale operating bioreactor landfills shows that these types of landfills can comply with existing Part 258 solid waste regulations and technical guidance. The addition of leachate and other liquids can be managed with appropriate design and operation of injection systems that evenly distribute the moisture within the waste. The design of leachate collection systems appear to be adequate to handle any additional leachate generated as all sites have been able to maintain leachate levels under 30 cm of head on the liner. Slope stability issues have been minor and are readily corrected. Proper design and operations also can provide for slope stability. Fires or “hot spots” appear to have greater potential in aerobic landfills but can be managed with good monitoring and prompt addition of liquids. The anaerobic bioreactors have similar issues as a normal landfill- balancing, tuning, and monitoring of the gas extraction systems.