

# **Bioreactor Landfills – An Innovative Technology for Biostabilization of Municipal Solid Waste**

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## **ABSTRACT**

The bioreactor landfill is a concept that has recently attracted interest, especially in North America. In contrast to conventional “dry tomb” landfills, bioreactor landfills provide favourable conditions for microbes to biologically stabilize waste within a relatively short period of time. This is mainly achieved by leachate recirculation, introduction of additional moisture and enhancing other factors that promote bioactivity. Advantages of bioreactor landfills, such as increased landfill gas generation providing opportunities for energy recovery, leachate treatment, potential for air space recovery, greenhouse gas emission reduction, and reduced post-closure monitoring costs, have sparked more interest among solid waste management personnel.

The City of Calgary sustainable landfill bio-cell (LBC) is a modified version of a bioreactor landfill. The LBC project is a full-scale pilot study fully funded by the City of Calgary Waste & Recycling Services Business Unit. It is designed to be operated under sequential anaerobic-aerobic conditions to incorporate advantages of both anaerobic and aerobic biodegradation. The development of the LBC provides the City of Calgary with a sustainable solid waste management option.

## **INTRODUCTION**

Landfilling is currently the primary disposal method of municipal solid waste (MSW) in North America. Approximately 75% of the MSW generated in Canada is disposed in landfills (Jackson, 2003). However, in the hierarchical Integrated Solid Waste Management, landfilling has a lower preference than waste reduction, reuse, or recycling including composting. Lower cost and availability of land (although this is becoming increasingly an issue) have made landfilling the most common waste management option in North America.

Two main concerns associated with landfills are leachate and landfill gas. Potential environmental, health and safety issues related to leachate and landfill gas require reliable control measures. Landfills attempt to manage these problems by designing and operating them as “dry tombs”. Designed with a low permeable containment and a leachate collection system at the bottom and a low permeable final cover at the top, conventional landfills minimize moisture infiltration and groundwater contamination. Prevention of wet conditions within a landfill directly reduces leachate generation and minimizes landfill gas generation by slowing down the process of waste biodegradation.

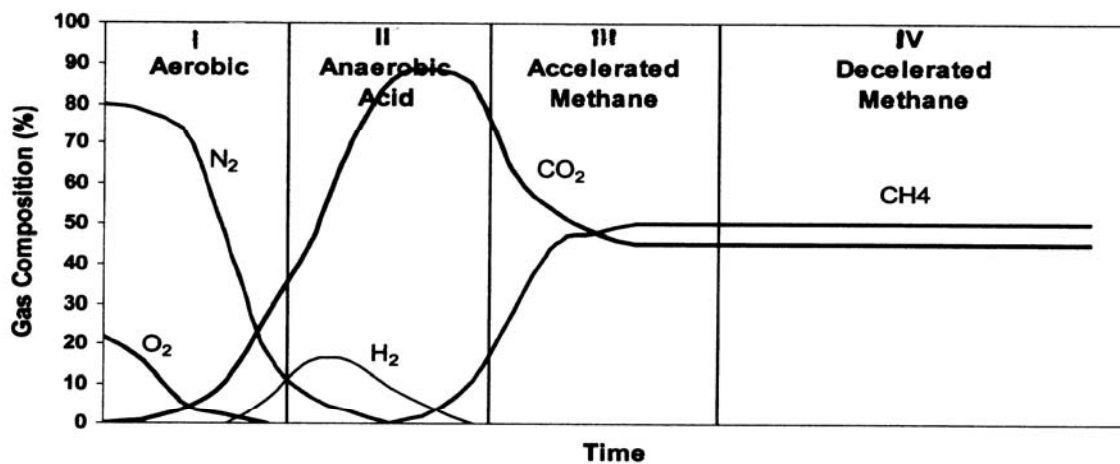
Due to these controls waste stabilization would occur very slowly under dry conditions and this process could continue for several decades. The fact that organics component in MSW could account for approximately 70% of the total waste (US EPA, 1995) complicates the situation causing further slow down in waste biodegradation.

During the last couple of decades there have been attempts to increase the rate of waste decomposition in a landfill setting. Leachate recirculation has been practiced in some landfills as a means of leachate treatment with the added benefit of faster waste stabilization. This concept has recently been extended to add supplementary moisture (in addition to leachate recirculation) in a controlled environment giving birth to the new landfill bioreactor concept. Recent advances in landfill research have indicated that the operation of landfills as bioreactors is a viable option for solid waste management (Reinhart and Townsend, 1998).

### BIO-STABILIZATION OF MSW

Organic component of the MSW is required to be stabilized before it is rendered harmless to the environment or human health. Biostabilized waste would not generate leachate or landfill gas in quality and quantity that will cause a threat for the environment and human health.

Biodegradation of waste in a landfill, following capping, is usually explained as a four-phase time sequence, which uses gas generation as the metric to distinguish between phases (Palmisano and Barlaz, 1996). The sequence is broken into an aerobic phase, an anaerobic acid phase, an accelerated methane production phase and a decelerated methane production phase. Oxygen entrapped in waste will be utilized by aerobic microorganisms in a short time period. Then it goes through an acid phase, which results in lower pH values. Methane production phase is the most important and longest process occurring in a landfill. This process could take many years to complete in a conventional landfill. Figure 1 presents typical biodegradation phases of waste within a landfill.



**Figure 1.** Generalized phases of MSW decomposition in a landfill

During the anaerobic phase methane and carbon dioxide is generated approximately in equal proportions. Aerobic phase requires oxygen for organic biodegradation and the gaseous byproducts during this phase include only carbon dioxide.

Organic component of MSW in a landfill should go through all these phases to become a biostabilized product. Restricting moisture input into a landfill affects the reaction rates of these processes and slows down decomposition. Under optimal conditions, these processes occur at a rapid rate, making the waste a biostabilized product.

## **CONVENTIONAL LANDFILL ISSUES**

Traditionally the intent of landfilling has been to provide a solution for solid waste disposal, which incorporated an “out of sight, out of mind” philosophy. Containment and management of leachate and landfill gas were integrated into the solution to deal with these unavoidable concerns. While dealing with these issues to minimize risks, conventional landfills neglected waste biostabilization, which is ultimately required to make waste harmless.

Landfills at present perform excellently to reduce short-term risks associated with leachate and landfill gas. When capped properly, they demonstrate reduction in leachate and landfill gas generation rates. However, waste buried within a landfill could be in a biologically dormant situation, waiting for an opportunity to be active when provided with favourable conditions. This is more critical in arid or semi arid climates as there is not sufficient moisture for waste decomposition. Since the conventional landfills do not try to convert waste into biostabilized end product, a failure in the capping and containment system (even after several decades) could start generation of leachate and landfill gas in significant quantities.

Emissions from landfills are one of the largest anthropogenic sources of atmospheric methane (CH<sub>4</sub>) in developed countries. In Canada, approximately 25% of anthropogenic CH<sub>4</sub> emissions are from landfills (Environment Canada, 2002). Not only does LFG contribute to greenhouse emissions, it is also a lost source of energy.

There are also other problems associated with the “dry-tomb” approach to managing solid waste. Specifically, conventional landfills do not address space issues, as the air space is filled once, then closed. Since the biodegradation of waste is not encouraged, recovery of space is not practical. The availability of landfill space is increasingly an issue in Canada, particularly in urban centres. Municipalities are constantly looking for methods to maximize the use of available landfill airspace, while trying to reduce the amount of materials that occupy landfill cells.

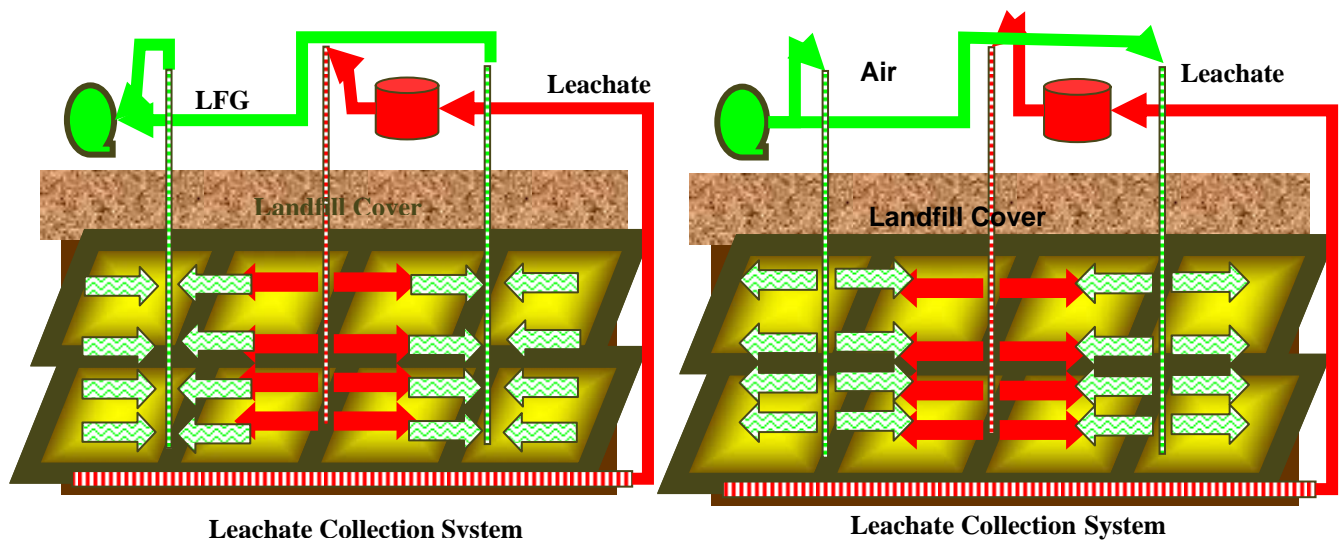
These issues associated with conventional landfills has encouraged researchers and waste managers to look for solutions which are more sustainable and has lower risks in the long term. Bioreactor landfill, a deviation from the “dry tomb” philosophy, but still an extension of landfilling, has sparked great interest among waste managers.

## BIOREACTOR LANDFILL CONCEPT

In contrast to conventional “dry tomb” landfills, landfill LBCs provide favourable conditions for microbes to biologically stabilize waste within a relatively short period of time (Pacey et. al., 2000). This is mainly achieved by leachate recirculation, introduction of additional moisture and enhancing other factors that promote bioactivity. Advantages of bioreactor landfills include increased LFG generation providing opportunities for energy recovery, leachate treatment, potential for recovery of air space, compost and other recyclables, greenhouse gas emission reduction, and reduced post-closure monitoring costs.

Bioreactor landfill concept considers landfill cells as “treatment vessels”. Organic component of the solid waste is biodegraded under optimal conditions. Addition of supplementary moisture increases the biodegradation process and recirculation of leachate allows transport of moisture, nutrients and microbes to different areas of the cell. In addition to the biostabilization of organic component of the solid waste, leachate in a bioreactor landfill is also treated during recirculation, thus avoiding leachate treatment costs.

Bioreactor landfills could be operated under either anaerobic or aerobic conditions. Figure 2 presents a comparison of anaerobic and aerobic bioreactor landfills. Anaerobic bioreactor landfills generate methane at a considerably higher rate compared to a conventional landfill providing opportunities for energy recovery. Aerobic bioreactor landfills decompose waste at a faster rate but requires a significant amount of energy to inject air into the system (Stessel and Bernreuter, 2001).



**Figure 2.** Schematic Diagrams of Anaerobic and aerobic bioreactor landfills

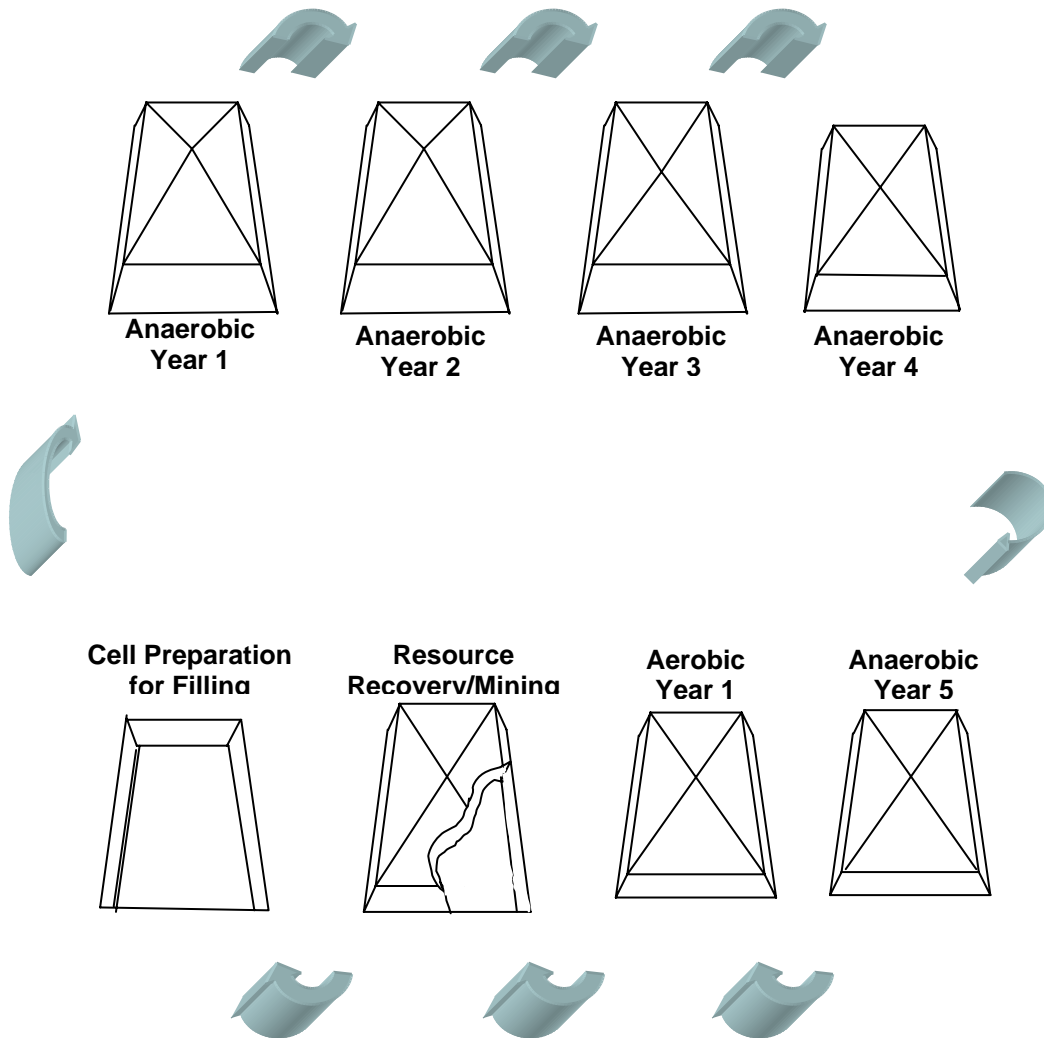
## **CASE STUDY: CITY OF CALGARY LANDFILL BIO-CELL PROJECT**

The City of Calgary decided to evaluate the potential of bioreactor landfills to provide a sustainable and environmentally friendly solution for MSW management. After a substantial literature review (University of Calgary, 2002) and discussions, the City decided to build a full-scale pilot landfill bio-cell. The bio-cell is an extension of the bioreactor landfill concept and incorporates advantages of both anaerobic and aerobic decomposition. It also provides a sustainable solution for waste management by allowing resource recovery and reuse of cell infrastructure. The uniqueness of the project inspired to develop a novel term sustainable landfill bio-cell (LBC). The LBC #1 was constructed in 2004 and is currently being filled. The project is fully funded by the City of Calgary Waste & Recycling Services Business Unit.

The City of Calgary LBC is designed to accept 55,000 tonnes of residential and commercial organic wastes and about 30,000 wet tonnes of digested sludge (Stantec, 2003). Digested sludge at approximately 8% moisture is the supplementary moisture source to achieve optimum moisture content. The LBC is designed as a full-scale facility that covers an approximate area of 100 m x 100 m with a waste footprint of 85 m x 85 m and a maximum height of 18 m.

The LBC will be operated in three phases: anaerobic, aerobic, and mining (resource recovery). It will be operated in anaerobic mode during first few years. Leachate will be recirculated and LFG will be collected and directed to the Shepard LFG utilization facility for energy recovery. When the gas generation is decreased to a point it is no longer economical to collect gas, the LBC will be converted to aerobic mode by injecting air into the cell using the same infrastructure used for gas collection. Leachate recirculation will be continued for aerobic microbes. Aerobic phase will continue until the waste is sufficiently stabilized so the leachate strength is low. Once it is determined that waste is stabilized the cell will be mined for compost material and other recyclables. It is anticipated the anaerobic phase will last 5-6 years and aerobic phase 1-2 years.

The City of Calgary sustainable LBC project envisions the construction of 7 or 8 LBCs consecutively, so that each cell is operating at anaerobic, aerobic, mining, or filling phase. Once a cell is mined, it will be inspected for integrity of the containment and leachate collection system for re-use. This innovative life cycle of the LBC provides sustainability to the LBC concept. Figure 3 illustrates the cycle of sequential anaerobic and aerobic operation of the LBC, resource recovery and reuse of cell infrastructure.



**Figure 3.** Sustainability concept in the LBC project

### **LBC DESIGN**

The LBC is designed and constructed with the following components:

- Groundwater Control System
- Composite liner containment system
- Leachate collection System
- Liquid/leachate injection system
- LFG collection / air injection system
- Final Cover

## **Groundwater Control System**

The LBC is constructed below the seasonal high groundwater table. Therefore, the cell has been designed with a Groundwater Control System system. This system consists of a geocomposite material placed below the compacted clay liner of the composite liner of the cell.

During the construction period of the LBC and initial filling, groundwater control system is pumped as required to prevent uplift on the liner system. Under normal operational conditions, groundwater is not pumped out allowing it to build an inward gradient minimizing the potential for leachate leakage through the composite liner.

## **Liner System**

The composite liner system consists of a primary 80 mil High Density Polyethylene (HDPE) geomembrane liner and a secondary 1.0 m thick compacted clay liner.

The composite liner system is particularly effective in terms of containment capability due to the synergy gained when the two materials are used in combination. This synergy is a result of the different leakage mechanisms for geomembrane and compacted low permeability clay liners. When the two are used in combination and intimate contact occurs such that leakage through the geomembrane cannot readily spread out across the compacted clay liner, leakage through any hole or defect in the primary geomembrane liner will be effectively “plugged” by the clay liner beneath.

## **Leachate Collection and Removal System**

The LBC Leachate Collection and Removal System collects and removes leachate produced within the cell. This system prevents the build-up of leachate head on the liner system and allows for leachate recirculation. In the LBC, because the waste is pre-wetted and because leachate is recirculated, the potential for leachate generation is higher than in a conventional landfill.

The leachate collection system consists of a gravel drainage layer at the cell base and on the inner side slopes of the cell. In addition, a geocomposite layer will be installed below the gravel layer on the slopes. Gravel filled trenches containing perforated HDPE pipes direct collected leachate into the leachate collection sump. The potential for clogging in drainage gravel will be minimized by using large size gravel. An automated submersible pump system installed in the leachate sump to pump leachate into the liquid injection system.

## **Liquid Injection System**

The purpose of the Liquid Injection System is to maintain optimum moisture content within the waste matrix for both anaerobic and aerobic reactions by recirculating leachate and any additional moisture as required. The Liquid Injection System would be operated in conjunction with the Leachate Collection and Removal System.

Once the LBC is operating, the average flow rate of liquid injection should be approximately equal to the average flow rate to the leachate sump. This equilibrium condition needs to be adjusted to optimum and maintained, in order to prevent the biomass from becoming too wet or too dry.

Net moisture gains or losses to the system through precipitation, evaporation, or other causes can be balanced by the addition or removal of liquid from the LBC at the leachate collection sump.

### **Landfill Gas Collection System**

LFG generated during the anaerobic phase of the LBC operations is collected by the LFG collection piping system installed within the biomass.

The design for LFG Collection System consists of a combination of horizontal and vertical perforated pipes connected to a landfill gas header for power generation at the Shepard LFG utilization facility. The perforated pipes are placed in gravel trenches.

LFG generated within the LBC is at a higher temperature (maximum temperature is assumed to be 50<sup>o</sup> C) than the ambient temperature under almost saturated conditions. When LFG is extracted, the moisture in the gas produces condensate. This condensate is collected and disposed in order for the LFG collection system to operate properly. The LFG collection piping system header includes a condensate knockout tank at the lowest point of the piping system.

### **Air Delivery System**

The same piping system used for LFG collection, during the anaerobic phase (Phase I) of the LBC will be used for air delivery to the biomass during the aerobic phase (Phase II) of the LBC.

The air delivery system will be operated with the objective of maintaining a minimum 5% oxygen concentration within the biomass air voids. This will enhance aerobic biodegradation and minimize potential CH<sub>4</sub> generation. Air injection will be started following the removal of top three layers of the final cover including the LLDPE membrane. However, the bio cap layer will not be removed and it will act as an oxidative or a biofilter layer for the LBC. The removal of the top layers and air injection will be undertaken in stages to minimize fire hazards and odour problems.

### **Final Cover**

Final cover will be installed progressively as design grades are achieved. An innovative way of mitigating methane emissions into the atmosphere using a bio cover is incorporated into the final cover. Methanotrophic bacteria in the layer of compost/soil mixture oxidizes any methane escaping into the atmosphere. It also consists of a geocomposite and a Linear Low Density Polyethylene (LLDPE) membrane to accommodate landfill gas collection. Topsoil layer will be vegetated to prevent erosion.

## LBC CONSTRUCTION / CELL FILLING

LBC construction was started in June 2004. The cell excavation and initial infrastructure of the LBC was completed in December 2004. The following images present installation of different components of the cell. Prior to placement of wastes several sensors were installed on the liner for monitoring.



**Figure 4.** Compacted clay liner and HDPE liner of the cell



**Figure 5.** Sensors to measure leachate level, temperature and settlement

Cell filling was started in May 2005. The cell is filled in three lifts of 5-6 m deep. Waste is horizontal layer and only compaction is during the dozer pushing waste. Back and forth movement of the dozer found to break the plastic bags exposing waste to moisture and microorganisms, which is very important to ensure complete biodegradation. Each lift is covered with a bio cover intermediate cover to minimize methane emissions during cell filling. Hydro mulch has been used innovatively as the daily cover to minimize litter and odour problems. Currently waste filling operation is continued and the LBC is approximately half full.

## LBC OPERATION

In contrast to a conventional landfill the LBC will be operated as a controlled system. The biological processes occurring within the LBC will be controlled to optimize the waste degradation and landfill gas generation. This process control will be achieved by monitoring the LBC. The main process controls involve varying the liquid injection rate and gas collection/air injection rate to the different zones of the LBC.

The main process control parameters for the LBC are temperature and gas composition at different locations in the cell. These parameters will be used to control liquid injection and LFG collection/air injection. Depending on the success and reliability of moisture measurements, moisture content of the waste will also be used in controlling liquid injection.

### **Phase I Operations**

During Phase I, the LBC will be operated to maximize CH<sub>4</sub> generation, collection and utilization. Liquid injection will be carried out throughout this phase to enhance biodegradation of the biomass. Liquid injection system will be adjusted by controlling individual valves to reduce non-homogeneity of moisture distribution within the LBC. Distribution of moisture will be monitored by moisture, temperature, and gas composition sensors/instrumentation.

LFG collection system will also be operated during phase I. Maximum LFG generation is expected soon after capping the LBC and will decrease with time. LFG collection system will also be controlled to collect maximum amount of gas and to prevent air ingress due to the vacuum applied. The anaerobic phase of the LBC will be terminated when it is no longer economical to operate the LFG utilization system.

### **Phase II Operations**

Conversion from Phase I to Phase II must be completed with care due to the potential for explosive gas mixtures (Reinhart and Townsend, 2001). There is also a higher potential for odour problems during this transition period. The removal of the top three layers of the final cover and air injection will be conducted in stages. During the transition period, some of the piping will be used for LFG collection to flare while others are being used for air injection.

Liquid injection will be continued in the Phase II. Liquid injection and air injection will be balanced to minimize power consumption and optimize aerobic biodegradation at the same time (for example, higher liquid injection rate will flood the pore spaces of the biomass making it difficult to inject air). Air injection will be operated to maintain the oxygen concentration within the biomass above 5%.

Phase II operations will be carried out until the biomass is stabilized in such a way that the final product or leachate does not cause any substantial environmental or human health impact.

### **Monitoring of the LBC**

Monitoring for the LBC consists of two components: regulatory requirements and process control requirements. Monitoring as per regulatory requirements aims at protecting human health, safety, and environment. Monitoring required for process control is for the proper operation of the facility as per the project objectives. These objectives include enhancing biodegradation of the LBC feedstock generating higher rate of LFG and faster feedstock stabilization.

## **CONCLUSION**

Bioreactor landfill concept is an attempt to reduce the risks associated with conventional landfilling. Compared to decomposition occurring in a conventional landfill, complete biostabilization of waste within a bioreactor landfill allows waste to be treated as a resource. The sustainable landfill bio-cell technology, which is an extension of bioreactor landfill, has the potential to improve on bioreactor landfill concept and to introduce sustainability to solid waste management.

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