Bioreactors Land-Fills (BRLFs) for Waste Treatment. 
(1) Its Main Characteristics and Advantages

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ABSTRACT
Bio-Reactors Landfills (BRLFs) represent important advancements over the classical Dry Land-Fills (DLFs) which are oldest technology for disposal of solid waste; specially Municipal Solid Waste (MSW). The combined use of laboratory experimental work and mathematical/computer modeling represents the best way for scaling-up to the design of commercial units and optimization of design and operation. This is the first part of a series of papers that introduces these relatively modern BRLFs; its main characteristics and the basic principles for its mathematical modeling using chemical reaction engineering rules in a rigorous manner. It also gives a couple of commercial cases to materialize the principles presented in the paper.

Keywords: Bio-reactors Landfills, Bio-gas, Methane, Biomass, Solid mass degradation, Leachate recycling
1. Introduction

The entire world, especially big cities, is suffering from the problem of solid waste including Municipal Solid Waste (MSW) and its different components with different degrees of Moisture Content (MC) and other wastes such as slaughter waste, paper waste, plastic waste, etc. In addition the sewage waste is another problematic one imposing a burden on the infrastructures of most cities around the world. Each class of waste lend itself to a certain Waste Treatment Technology (WTT) according to its characteristics which are usually the basis for their classification before choosing the optimal WTT.

Many cities face peak periods when the waste is much higher than the average of the rest of the year; therefore Waste Treatment Facilities (WTFs) should be designed to accommodate the average yearly waste as well as the waste of the peak period. The MSW, including food and lignocelluloses waste together with other sources of waste, e.g.: slaughter and sewage sludge, etc. can be fed to landfills and biogas for energy production extracted from its bio-degradation.

An excellent way to treat these huge amounts of these types of waste is the modern “Bi-Reactors Land-Fills” (BRLFs) in contradistinction to classical ordinary “Dry-Land-Fills” (DLFs). The main difference between the BRLFs and DLFs is the circulation of Leachate Fluid (LF) in the case of the BRLFs making the rate of degradation faster and the rate of gas production for electricity generation higher (Glass, 2007). The BRLFs concept is relatively new and is subjected to extensive modern Research and Development (R&D); USA Departments Of Energy (DOE) and Environmental Protection Agency (EPA) are investing extensively on the R&D of this technology (County, 2003; Oldenburg, 2001; EPA USA, 2007). A simple schematic diagram for a BRLF is shown in Fig.1. Also a schematic simplified diagram for a slightly different BRLF is shown in Fig.2. For designs and modern applications the gas is not flared but used as a source of energy and the BRLF is optimized for this purpose.

Fig.1. Bioreactor Landfill (SCS)
Fig. 2. Simple Schematic diagram for a typical BRLF (Kerry et al.) (Notice that in modern application the gas is not flared but used as a source of energy and the BRLF is optimized for this purpose)

The BRLF technology is sensitive to the type and characteristics of the waste used and no clear guides for design and operation are yet to be developed and therefore every new project is accompanied by a parallel laboratory scale research to decide basic design and operation parameters. Optimally, this laboratory scale research should be turned from laboratory experiments to mathematical computer models suitable for scaling up, design, optimization and design/operation of the commercial scale unit.

The commercial scale unit is also to be used to improve the accuracy and reliability of these mathematical models and turns them into reliable design equations for duplication and optimization of more units. Also this work needs to be coupled to the development and choice of optimal microbes to accelerate the degradation reactions decreasing the amount of solid waste, increasing the amount and quality of gas for electricity production and amount of LF to be recycled to accelerate the biodegradation processes.

It is possible to use different strains of Fungi; algae and other microbes as bio-catalysts for these BRLFs. The use of algae will also allow the production of biodiesel from these algae which will grow in these BRLFs. These BRLFs can be completely aerobic and blowing air to bubble through it, or completely anaerobic (may be allowing a short period of aerobic at the beginning to finish the existing air) or a mixture of both simultaneously or sequentially.

This microbe choice is another challenge regarding the design and optimization of the BRLFs depending upon the nature and characteristics of the waste as well as the desired products.
2. Basic Characteristics of BRLFs

Many types of BRLFs can be addressed both on the laboratory and the commercial scales and also different approaches can be adopted to develop rigorous and reliable methods for the design, scaling-up, replication, optimization, etc. for these very promising units.

The laboratory scale units are used in order to obtain the necessary information for the rigorous design of the commercial scale units and these small units can be “batch” with respect to waste material and the solid residual after degradation but are not batch with respect to produced gas or LF.

With extra simplification we can consider the unit to be described by these four components and two reactions. The ultra-simplified components are: A= lumped waste mixture, B= lumped liquid (LF), C= lumped gas and D=lumped waste material remains. The two simplified reactions can be considered:

\[
\begin{align*}
\sigma_{A1} & \quad A \quad \rightarrow \quad \sigma_{D1} \quad D \quad + \quad \sigma_{B1} \quad B \quad + \quad \sigma_{C1} \quad C \\
\sigma_{A2} & \quad A \quad + \quad \sigma_{B2} \quad B \quad \rightarrow \quad \sigma_{D2} \quad D \quad + \quad \sigma_{C2} \quad C
\end{align*}
\]

\(\sigma_{ij}\) = stoichiometric number of component i in reaction j which are positive for products and negative for reactants. For component A they are \(-ve\) in both reactions, while for component B which is a product in reaction 1 and a reactant in reaction 2: \(\sigma_{B1} = +ve\) and \(\sigma_{B2} = -ve\). All the other stoichiometric numbers are +ve.

It is best to use these equations in molar form and whenever a mass of any component is required we just multiply the molar amount (or rate) of the component i by the Molecular Weight (MW\(_i\)) of component i, i.e.: \(m_i\) (mass or mass flow rate) = \(n_i \cdot MW_i\).

From the simplified lumped system above, main wastes A and remains D are both batch amounts but B and C cannot be considered batches. C is an evolving gas depending upon its production from reactions 1 and 2, while B can be produced if its production in reaction 1 is higher than its consumption in reaction 2 and vice versa; however it has to be noticed that if the amount of B is zero it cannot be consumed any further.

The recycle of B to this simplified semi-batch BRLF allows certain control of the B content inside the experiment and allows investigation of the % content of B on reaction 2 and the overall balance taking into consideration this recycle. Removal of B without recycle is usually used as standards (controls) cases to compare and show the effect of B recycle (Hernandez-Berriel, 2010).

The rate of removal of C and of B (with or without recycle) for the mass of the experimental BRLF depends upon the technique of their removal and differs from that in the commercial units; but in both cases the rate of removal of C and B is related to their amounts in the BRLF.

For the present time it is considered that rate of B removed= \(n_{B\text{out}}\) (moles/day)= \(\alpha_B \cdot n_B\) and rate of removal of C = \(n_{C\text{out}}\) (moles/day)= \(\alpha_C \cdot n_C\) units of \(\alpha_B\) and \(\alpha_C\) are (1/day).

According to the above the differential equations describing the dynamics of this system are:
\[ \frac{dn_i}{dt} = \sum_{j=1}^{\sigma_{ij}} r_j - W_i \]

Where i are the 4 components: A, B, C, and D and j are the reactions 1 and 2 and \( W_i \) is the net removal rate of component i; for A and D it is zero and for C it is \( \alpha_C \cdot n_C \) and for B it is \( \alpha_B \cdot n_B(1 - \varepsilon) \); where \( \varepsilon \) is the fraction of output \( n_B \) (\( n_{B_{out}} = \alpha_B \cdot n_B \)) recycled to the BRLF.

For \( \varepsilon = 0 \) there is no recycle (standard(control)) calibration cases to compare with recycle cases to study effect of recycle; and \( \varepsilon = 1.0 \) means complete recycle of the produced B (LF) and no net output of it from the unit.

The initial conditions for the above 4 differential equations are: at \( t=0 \), \( n_i = n_{i0} \).

Laboratory BRLF experiments can also use recycling continuously as discussed above but in the form of equivalent discrete recycling, e.g.: collecting B (LF) in a tank over the period (e.g.: a week or less or much longer) and then add it all or a fraction of it at the end of the period (Hernandez-Berriel, 2010; Bareither, 2012). Preliminary investigation of these two techniques of recycling shows that they do not differ much with regard to the overall behavior. More research is needed regarding these two recycling approaches for both laboratory scale, pilot plant and commercial scale units (Elagroudy, 2009; Rendra, 2007).

Of course the actual situation is more complicated than the above over-simplified 4 components; 2 reactions systems. Usually a reasonable representation include 11 components; 6 reactions system and it differs from one type of waste to the other and from one type of microbes used to the other and requires the development of reasonably reliable rates of reaction bio-kinetic equations and investigate both semi-batch process as described above as well as continuous processes including continuous (or discrete) addition of waste (A or multi-components waste) and continuous (or discrete) removals of waste reminders (D or multi-components reminder of the waste components); optimizing the LF recycle rate and maximize the gas production to operate an electric generation plant based on this gas. It should also include the growth of the micro-organisms catalyzing the bio-degradation reactions.

3. Background Material and Applied Examples

As described briefly at the beginning, the suggested waste for this type of modern BRLF is includes mainly: food+ lignocelluloses + other wastes such as slaughter waste, etc. These are huge amounts all over the world especially in large cities and some cities have their peak periods during the year for different reasons (e.g.: pilgrimage, tourism, etc.).

Landfills and their associated degradation bioreactors do not only produce gasses for energy generation and LF which can be used as a recycle stream to optimize moisture contents and maximize production of gasses but also it cause land settlement which affect the use of the land of large scale units for construction and other purposes (El-Fadel and Khoury, 2000).

All types of Landfills specially the modern BRLF remain an attractive disposal route for MSW because in most cases it is more economical than other alternatives such as incineration and composting.

The post closure DLFs uses large areas to bury the waste for a long time and these areas are used for urban applications when development of landfilled areas becomes essential as urban
growth reaches landfill boundaries. Physicochemical and biological processes hinder the beneficial use of such lands because of gas and LF generation coupled with significant settlement (Valencia, 2009). The rate and magnitude of landfill deformations are often non-uniform resulting in differential settlements that can have devastating effects on the integrity of any structure erected on the landfill. Differential settlements also eventually result in problems such as surface ponding, development of cracks, and failure of the cover system, including tearing of geo-membranes, as well as damage of gas collection and drainage pipes. The ability to predict settlement becomes a key issue in the design and construction of landfills.

BRLFs offer a different solution which is associated with the acceleration of the waste materials consumption; increasing the gas produced for energy consumption as well as increasing the LF and recycling an optimal fraction of it to maximize bio-degradation and gas production. Therefore settlement accompanying the waste degradation becomes a desirable factor in BRLFs (Visvanathan, 2010; Wen-Wei Li and Han-Qing Yu, 2013).

The BRLFs aimed at include the waste types mentioned above in addition to a small amount of sewage waste (1-2% of the total mass of the waste), this is not to contribute to the water (Moisture Content, MC) of the waste for this is achieved and optimized using the LF production and recycle. This small % of sewage waste is added as an additional source of microbes. Research is needed to investigate these types of microbes in this small amount of sewage and their influence on the main microbes used. It is also important to investigate the possibility to use algae as the main microbe and the possibility of producing biodiesel from these growing algae. Other aspects need to be explored including the use of fungi as microbe for degradation and the associated useful bio-products, dark fermentation, production of bio-hydrogen (WEN-WEI 2013)[14] and methane (Monlau, 2013), etc. and other useful products to improve the economics of the process making the waste an asset rather than a burden.

BRLFs require sufficient moisture to optimize the biodegradation processes and methane generation, since from energy point of view it is much better to produce CH₄ as a useful cheap fuel; than CO₂ which is a global warming gas. In desert areas this is problematic given the lack of fresh water supplies. Saline water, from the sea, can be used but may inhibit the biodegradation of the MSW in the BRLFs. Sludge, from waste water plants, may be used to enhance the biodegradation of MSW under saline conditions. Both the addition of a small % of sewage as briefly mentioned above and the possibility of using sea water with sludge need to be investigated to study the effect of each of them ( or both) on the rate of MSW degradation (Alkaabi, 2009).

Before addressing the subsections of research needed for developing a suggested typical BRLF we will cover briefly some of the characteristics of well-established and successful BRLFs in Calgary and another one in the USA as simple guides for suggested combined research and design of such units.

While DLFs in the US and Canada are by the hundreds, the modern BRLFs are only by the dozens, most of them in USA and the rest in Canada. From the few ones in Canada the one in Calgary-Alberta-Canada is quite successful (Perera, 2003).

Some light on the details of this successful BRLF will prove to be useful for the investigation of BRLFs suggested as the most promising WTT not only from waste disposal point of view but also from the point of view of renewable energy production utilizing waste.
For the DLFs and due to its main characteristics waste stabilization (degradation) would occur very slowly under dry conditions and this process could continue for several decades. The fact that organic components in MSW could account for approximately 70% of the total waste (US EPA. 1995) complicates the situation causing further slowdown in waste biodegradation using DLFs. On the other hand BELFs increase the rate of waste decomposition by setting LF recirculation as a means of leachate treatment with the added benefit of faster waste stabilization (degradation). This concept has recently been extended to add supplementary moisture (in addition to LF recirculation) in a controlled environment giving birth to the new BRLF concept.

Both main types of landfills are currently the primary disposal methods of MSW in USA, Canada, Europe and some countries of Mid-America (e.g.: Mexico) and other Latin American countries and will occupy its place in other countries around the world. Approximately 75% of the MSW generated in Canada is disposed in landfills (Duncan Bury Consulting, 2012) and similar percentages are in USA and other developed countries and lower in developing countries. 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 LF and Landfill Gas (LG), which are potential environmental, health and safety issues.

DLFs do not have a strong potential for solving and exploiting these problems; while BRLFs have this potential. Landfills attempted to manage these problems by designing and operating them as “dry tombs” (DLFs) but those trials were neither very promising nor successful. Some improvements regarding DLFs included: designs 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, etc. Prevention of wet conditions within a landfill directly reduces LF generation and minimizes LG by slowing down the process of waste biodegradation. While this is desirable in the classical DLFs (dry tomb), it is the opposite in modern BRLFs that are suggested and discussed here.

4. Main Issues and Challenges

BRLFs, have many advantages over DLF and will radically revolutionize the concept of landfills with regard to getting rid of certain classes of waste imposing themselves on humanity in huge quantities estimated in the billions of tons. However this is not the only big advantage of BRLFs but the very big advantage is with regard to the large of production of biogas suitable for energy production and as renewable as these huge amounts of waste are renewable and therefore contributes positively to Sustainable Development (SD). Exploiting the excellent advantages of BRLFs requires a deep understanding of its main characteristics as briefly shown below.

4.1 Bio-stabilization of MSW

Organic components of the MSW are required to be stabilized (degraded) before it is rendered harmless to the environment or human health. Bio-stabilized waste in a DLF does
generate neither LF nor LG in quality nor quantity that will cause a threat for the environment and human health and will also not be enough for economical and efficient energy generation.

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, 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 relatively 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 conventional landfills, however it will be much faster in a modern BRLFs.

Chemistry studies treat these stages as sequential stages, but biochemical engineering studies should investigate and compare the sequential phases and parallel phases modes for this is important regarding the bio-kinetics of the system and the development of reliable models as design and optimization equations, for there is no strong scientific reasons to suggest that each phase will “await” the completion of the previous phase in order to start. This is important from a fundamental point of view as well as from a practical engineering point of view.

The aerobic phase (if the phases are sequential) requires oxygen for organic biodegradation and the gaseous byproducts during this phase include only CO\(_2\) thus the main gas in the LG is CO\(_2\) while in the anaerobic phase CH\(_4\) is dominating the LG and CO\(_2\) is generated in much lower proportions. According to the sequential phases assumption; organic components of MSW in a landfill should go through all these phases to become a bio-stabilized product. Restricting moisture input into a landfill affects the reaction rates of these processes and slows down decomposition. Under optimal conditions of temperature and MC, these processes occur at a rapid rate, making the waste a bio-stabilized product.

4.2 Conventional Landfill Issues

Before more advanced issues are addressed regarding these modern BRLFs; conventional issues are addressed for they are the background of the modern issues and their associated BRLFs. Landfills at present perform excellently to reduce short-term risks associated with LF and LG. When capped properly, they demonstrate reduction in LF and LG 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 favorable conditions. This is more critical in arid or semiarid climates, where there is not sufficient moisture for waste decomposition. Since the conventional landfills do not try to convert waste into bio-stabilized end product, a failure in the capping and containment system (even after several decades) could start generation of LF and LG in significant quantities.

Emissions from landfills are one of the largest anthropogenic sources of atmospheric CH\(_4\) in developed countries. In Canada, approximately 25% of anthropogenic CH\(_4\) emissions are from landfills (Environment Canada. 2002). Not only does LG contribute to greenhouse emissions, it is also a lost source of energy. There are also other problems associated with the “dry-tomb” approach for managing solid waste. Specifically, conventional landfills do not address space issues, as the air space is filled once and 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, USA and other countries particularly in urban centers. 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 have encouraged researchers and waste managers to look for solutions which are more sustainable and has lower risks in the long term. BRLFs, a deviation from the “dry tomb” philosophy, but still an extension of landfilling, has sparked great interest among waste managers.

4.3 The heart of the BRLF Concept

In contrast to conventional “dry tomb” landfills, BRLFs provide favorable conditions for microbes to biologically stabilize waste within a relatively short period of time (Pacey, 2000; Purdy and Shedden, 2008). This is mainly achieved by LF recirculation, introduction of additional moisture and enhancing other factors that promote bioactivity.

Advantages of BRLFs include increased LG generation providing opportunities for energy recovery, LF treatment, potential for recovery of air space, compost and other recyclables, greenhouse gas emission reduction, and reduced post-closure monitoring costs.

BRLFs concept considers the unit as “treatment vessel(s)” (Bio-reactor(s)). Organic components of the solid waste are biodegraded under optimal bio-catalytic conditions. Addition of supplementary moisture increases the rate of the biodegradation process and recirculation of LF allows transport of moisture, nutrients and microbes to different areas of the cell (the heart of the BRLF containing the solid waste). In addition to the bio-stabilization of organic components of the solid waste, LF in BRLF is also treated during recirculation, thus avoiding LF treatment costs.

BRLFs could be operated under either anaerobic or aerobic conditions; as explained earlier. The anaerobic operation produces more CH$_4$, while the aerobic operation produces more CO$_2$ (Stessel and Bernreuter, 2001).

5. Landfill Biological Cell (LBC)

LBC is formed of all the components of the BRLF in addition to additional parts that make it efficiently operating. A typical picture of an LBC is shown below in Fig.3.

5.1 Groundwater Control System

The Landfill Biological Cell (LBC) is an extension of BRLF. It is constructed below the seasonal high groundwater table. Therefore, the cell is designed with a Groundwater Control System (GCS). This system consists of a geo-composite material placed below the compacted clay liner of the composite liner of the cell.

During the construction period of the LBC and initial filling, GCS 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 LF leakage through the composite liner.
5.2 Liner System

The composite liner system consists of a primary 80 mil High Density Poly-Ethylene (HDPE) geo-membrane 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 geo-membrane and compacted low permeability clay liners. When the two are used in combination and intimate contact occurs such that leakage through the geo-membrane cannot readily spread out across the compacted clay liner, leakage through any hole or defect in the primary geo-membrane liner will be effectively “plugged” by the clay liner beneath.

5.3 LF Collection and Removal System

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

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

5.4 Liquid Injection System (LIS)

The purpose of the LIS is to maintain optimum moisture content within the waste matrix for both anaerobic and aerobic reactions by recirculating LF and any additional moisture as required (sewage, sludge, etc.). The LIS is operated in conjunction with the LF Collection and Removal System. Once the LBC is operating, the average flow rate of liquid injection becomes 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.
6. Case Studies

Based on the above basic principles two case studies are presented, one in Canada and the other in the USA. The purpose of these two case studies is to materialize the above principles to practical cases in order to conclude the laboratory research information necessary to build a new BRLF and the optimal use of mathematical/computer modeling coupled to experimental results.

6.1 Case Study 1 (City of Calgary-Alberta-Canada, BRLFs)

The City of Calgary decided to evaluate the potential of BRLF 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. As briefly explained above, the bio-cell is an extension of the BRLF 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 and filled in 2004/2005. 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. As discussed above sewage and/ or digested sludge can be used as a source of moisture together with recirculated LF and also as an additional source of microbes to accelerate degradation.

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. LF is recirculated and LG is collected and used for energy recovery. Once it is determined that waste...
is stabilized the cell is mined for compost material and other recyclables. Anaerobic phase can last 5-6 years and aerobic phase 1-2 years.

The City of Calgary sustainable LBC project constructs 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 (ILC) of the LBC provides sustainability to the LBC concept.

6.1.1 The LBC is design

The LBC is designed and constructed with the following components:

- Groundwater Control System (GCS)
- Composite liner containment system
- LF collection system
- LF injection system
- LG collection / air injection system. The air is for alternating between anaerobic and aerobic cycles
- Final Cover Anaerobic Year 1 Anaerobic Year 2 Anaerobic Year 3 Anaerobic Year 5 Anaerobic Year 4 Resource Recovery/Mining Aerobic Year 1 Cell Preparation for Filling.

6.1.2 LG Collection System

LG generated during the anaerobic phase of the LBC operations is collected by the LG collection piping system installed within the main body of biomass. The design for LG collection system consists of a combination of horizontal and vertical perforated pipes connected to a landfill gas header for power generation in a generation facility. The perforated pipes are best to be placed in gravel trenches. LG generated within the LBC is at a higher temperature (maximum temperature is about 500 C) than the ambient temperature under almost saturated conditions. When LG is extracted, the moisture in the gas produces condensate. This condensate is collected and disposed in order for the LG collection system to operate properly. The LG collection piping system header includes a condensate knockout tank at the lowest point of the piping system.

6.1.3 Air Delivery System

The same piping system used for LG collection, during the anaerobic phase (Phase I) of the LBC is to be used for air delivery to the biomass during the aerobic phase (Phase II) of the LBC. The air delivery system is operated with the objective of maintaining a minimum 5% oxygen concentration within the biomass air voids. This will enhance aerobic biodegradation and minimize potential CH₄ generation. Air injection starts 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 bio-filter layer for the LBC. The removal of the top layers and air injection will be undertaken in stages to minimize fire hazards and odor problems.
6.1.4 Final Cover

This is installed progressively as design grades are achieved. An innovative way of mitigating CH$_4$ emissions into the atmosphere using a bio-cover is incorporated into the final cover. Methanotrophic bacteria in the layer of compost/soil mixture oxidize any CH$_4$ escaping into the atmosphere. It also consists of a geo-composite and a LLDPE membrane to accommodate BRLF gas collection. Topsoil layer is vegetated to prevent erosion.

6.1.5 LBC Construction/Cell filling

LBC construction in Calgary-Canada was started in June 2004. The cell excavation and initial infrastructure of the LBC was completed in December 2004. Cell filling was started in May 2005. The cell as 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 odor problems. Currently waste filling operation is continued and the LBC is approximately half full.

6.1.6 LBC Operation

In contrast to a conventional (dry) landfill the Calgary-LBC is operated as a controlled system. The biological processes occurring within the LBC are controlled to optimize the waste degradation and LG generation. This process control is achieved by monitoring the LBC. The main process controls involve varying the LF 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 are used to control liquid injection and gas collection/air injection. Depending on the success and reliability of moisture measurements, moisture content of the waste is used in controlling liquid injection.

6.1.7 Phase I Operations

During Phase I, the LBC is operated to maximize CH$_4$ generation, collection and utilization. Liquid injection is carried out throughout this phase to enhance biodegradation of the biomass. Liquid injection system is 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.

Gas collection system is also operated during phase I. Maximum gas generation is achieved soon after capping the LBC and decreases with time. Gas collection system is also controlled to collect maximum amount of gas and to prevent air ingress due to the vacuum applied. The anaerobic phase of the LBC is terminated when it is no longer economical to operate this gas utilization system producing mainly CH$_4$. 
6.1.8 Phase II Operations

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

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

Phase II operation is 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.

6.1.9 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 and quality of gas and faster feedstock stabilization.

This Calgary case shows that BRLF is an attempt to reduce the risks associated with conventional landfilling. Compared to decomposition occurring in a conventional landfill, complete bio-stabilization 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 BRLF has the potential to improve on bioreactor landfill concept and to introduce sustainability to solid waste management.


This is a USA BRLF and the principles of establishing it is not very different from that of Calgary-Canada case therefore only its facts and numbers are reported as shown below.

6.2.1 Williamson county bioreactor fact sheet

6.2.1.1 Waste footprint = 6 acres (2.43 hectares) at base
6.2.1.2 Maximum waste depth is approximately 40 feet (12.2 meters)
6.2.1.3 Total original waste tonnage = 69,880 short tons or 63,394 Mg

In the UK, short tons are rarely used. The word ton is taken to refer to a long ton, and metric tons are distinguished by the tonne spelling. Most Commonwealth countries followed British practice with the exception of Canada, which used short tons in preference to long tons, as in the USA. In the USA it is often called simply ton without distinguishing it from the tonne (1,000 kilograms or 2,204.62262 pounds) or the long ton (2,240 pounds or 1,016.0469088
kilograms); rather, the other two are specifically noted. There are, however, some USA applications for which unspecified tons normally means long tons (for example, Navy ships) or metric tons (world grain production figures). Both the long and short ton are defined as 20 hundredweights, but a hundredweight is 100.000000 pounds (45.359237 kg) in the USA system (short or net hundredweight) and 112 pounds (50.80234544 kg) in the imperial system (long or gross hundredweight). If you are an American, when you refer to a ton, you probably mean the short ton of 2,000 pounds as opposed to the UK ton -- the long ton -- of 2,240 pounds. Neither of these tons has any exact equivalent in the metric system. At 2,204.6 pounds, the metric ton falls between the short ton and the long ton. Once you learn these numbers, converting between the three types of tons becomes a fairly simple process.

6.2.1.4 Shape of subject area resembles a truncated pyramid with steep side slopes (Avg 1.5:1). A bit similar to Fig.3 above

6.2.1.5 Retrofit operation only. No pre-processing of wastes occurred before placement. No new waste placement is taking place

6.2.1.6 Site has been operating continuously as a forced aeration BRLF since October 17, 2000 (with periodic shut downs for maintenance and repair)

6.2.1.7 LF and occasionally storm water, is pumped into the mass via vertical screened wells.

6.2.1.8 This is a “temperature feedback” operation

6.2.1.9 Three 1000 acfm (28.3 m³/min) blowers are utilized on site

6.2.1.10 Compressed air is injected into the waste via vertical screened wells

6.2.1.11 Average air injection = 27.5 acfm per well

The BRLF being an aerobic one, means that it will produce mostly CO₂ and not CH₄ and will therefore not be a source of energy; but further parallel research can make CO₂ a source of valuable CNTs and O₂. Such an aerobic BRLF requires good control over LF and LG production and good efficient collection of both of them and optimal circulation of LF.

7. Suggested Research Steps Associated with Construction of a New BRLF

The above principles and two case studies shows that BRLFs and their extension to LBCs are not like other chemical and biochemical processes. Their design and operation requires parallel research, scaling up and optimization. The very nature of BRLFs and LBCs make them related to parallel research related to each case. This is because of the Multi-Disciplinary (MD) nature of the process and its sensitivity to the nature of the waste used in the specific BRLF/LBC and the microbes utilized for the degradation. The BRLF/LC suggested for a certain case requires the following:

- Suggest the type and quantities of waste to be used. The preliminary suggestion includes: MSW including lignocelluloses from MSW+ lignocelluloses from other industrial and non-industrial sources+ Food, both municipal and non-municipal + Slaughter waste + small amount of swage waste (1-2%), not as a source of water since this is provided through recycled LF but as a source of microbes to bio-catalyze degradation + additional microbes to maximize degradation.
• Estimating the amounts of the above components to be fed to the BRLF and their fluctuation between the normal and maximum periods.
• Building a laboratory scale unit and testing it for different chosen modes of operations.
• Develop a preliminary design for the suggested BRLF/LBC using relatively simple design equations to be improved during the research work at the laboratory level couple to mathematical/computer modeling.
• Checking the design equations against the laboratory scale unit; improving the design equations and adjust its design and operating parameters to make the design equations more reliable.
• Use the improved design equations to check the optimal conditions experimentally. At this stage the design/research team will be ready with reliable design equations to design a commercial unit, or go one further conservative step forward by designing and building a micro-pilot plant and improve the design equations further as last step before using it to build a commercial unit.

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