International Conference on Case Histories in Geotechnical Engineering

(2013) - Seventh International Conference on Case Histories in Geotechnical Engineering

02 May 2013, 4:00 pm - 6:00 pm

A Comprehensive Model for Anaerobic Degradation in Bio-Reactor Landfills

Jay N. Meegoda
New Jersey Institute of Technology, Newark, NJ

S. Bhuvaneshwari
New Jersey Institute of Technology, Newark, NJ

P. A. Hettiaratchi
University of Calgary, Canada

H. Hettiarachchi
Lawrence Technological University, Southfield, MI

Recommended Citation

Meegoda, Jay N.; Bhuvaneshwari, S.; Hettiaratchi, P. A.; and Hettiarachchi, H., "A Comprehensive Model for Anaerobic Degradation in Bio-Reactor Landfills" (2013). *International Conference on Case Histories in Geotechnical Engineering*. 2.
https://scholarsmine.mst.edu/icchge/7icchge/session_06/2

Commemorate the Legacy of Ralph B. Peck
April 29 - May 4, 2013 CHICAGO
Seventh International Conference on
Case Histories in Geotechnical Engineering
and Symposium in Honor of Clyde Baker

A COMPREHENSIVE MODEL FOR ANAEROBIC DEGRADATION IN BIO-REACTOR LANDFILLS

Jay N. Meegoda
New Jersey Institute of Technology
Newark, NJ-USA 07102

S. Bhuvaneshwari
New Jersey Institute of Technology
Newark, NJ-USA 07102

P. A. Hettiaratchi
University of Calgary
Calgary, Alberta, Canada, T2N 1N4

H. Hettiarachchi
Lawrence Technological University
Southfield, MI 48075

ABSTRACT

A new generation of sustainable landfill was designed and constructed in the City of Calgary, Canada to achieve sustainable municipal solid waste (MSW) management. This sustainable landfill called “biocell” involves sequential operation of a landfill cell to produce methane gas during the first stage of anaerobic degradation and in-situ composting within the cell footprint. Once methane recovery is minimal, the second stage aerobic degradation initiated by injecting air through methane recovery system and finally landfill is mined for resource and space recovery in the third stage. The resources that can be recovered include compost like material and recyclables such as plastics, metal, and glass. Non-recovered waste but with high energy content can be used as refuse derived fuel. The practice of this approach will no longer require the need to allocate valuable land for new landfills on an on-going basis. There is leachate re-circulation and environmental monitoring to enhance biodegradation in the biocell. The biocell eliminate problems of ground/surface water contamination, landfill gas emission and the need for new land to use for waste disposal. However, currently there is limited knowledge on landfill mining and in order to estimate the best time to initiate landfill mining a comprehensive mathematical model was developed.

The model developed solves the mass and energy balance of waste decay, which computes the rate of gas generation, change of gas and gas flux through the system. This study focuses on anaerobic phase of biodegradation of biomass and the degradation of the biomass was assumed to follow first order kinetics. The decomposing bio mass is represented as cellulose for energy balance computation, which is a major constitution of the MSW. The degradation of bio mass due to micro-organisms generates methane, carbon dioxide and water as the final products and the reaction is exothermic. In this model using the decay of waste computed from mass balance and cellulose as equivalent chemical representing the waste a relationship between the mass degraded with time was established. The heat released due to anaerobic decay is computed and hence computes the increase in biocell temperature. Then selecting the representative decay constant for the computed biocell temperature, the decomposition of waste was computed for the next time step. The above computation is continued in order to obtain the landfill settlement, temperature and the movement of landfill gas and leachate.

INTRODUCTION

A bioreactor landfill is a sanitary landfill that uses enhanced microbiological activity to transform and stabilize the readily and moderately decomposable organic waste constituents within 5 to 10 years of land-filling. The enhancement in biodegradation is usually achieved by recirculating the leachate collected from the bottom of the landfill. The recirculation helps in cycling of the microbes and nutrients into the medium and maintains optimum moisture levels in the landfill.

The faster degradation rate causes higher rates of settlement in the bioreactor landfills. The study of the settlement behavior of the landfill becomes very important due to its direct impact on the operation of the landfill. The additional space achieved through the settlement during the filling is a possible way to increase the landfill capacity. It also becomes important to evaluate the impact of the rapid settlement on landfill components such as leachate recirculation systems and gas collection pipes networks (El-Fadel and Khoury 2000). The amount of the gas generated and the temperature changes are indirect measures of landfill activity, so when the decomposition becomes slower after the transition phase, the landfill can be mined to recover resources, and the utilization of the space created (Hettiaratchi et al., 2010). Hence the proper construction and maintenance planning of a bioreactor landfill requires the understanding of the behavior of the

MSW (Municipal solid waste) in a bioreactor landfill as well as the settlement and gas generation during construction and subsequent operation.

A landfill is an interacting system of multiphase media (gas, liquid, and solid) with each phase exhibiting spatial and temporal variations (Hiettiarachchi, 2005) Therefore, MSW settlement should depend on contribution from all three phases. This can be particularly important in bioreactor landfills due to the increased moisture and enhanced gas production. Gas transport models are based on the assumption that the landfill can be treated as a porous medium and the gas velocity is given by Darcy's law. Hettiarachchi et al., (2007) incorporated generation and dissipation of landfill gas into their settlement model, which also accounted for the bio degradation of MSW. The heterogeneity of the MSW was also considered based on their degradability.

The engineering properties of the waste are considerably affected by the temperature in the landfill. Heat is generated as a result of the biochemical processes and decomposition of the organic components in the waste. Elevated temperatures significantly affects the microbial function and thereby the overall operation of the landfill. In order to simplify the calculations of heat generation, the rate of heat produced could be related to the rate of acid produced (Hettiarachchi, 2007). Optimum temperature ranges for maximum gas production from waste decomposition were identified to range between 34 and 41°C in laboratory studies. Though considerable studies has been carried out on the gas generation and settlement occurring in a landfill, detailed spatial heat distributions or comprehensive long-term thermal trends are not available for landfills, studies on analysis of heat generation and temperature distribution has been limited.

THE CALGARY BIOCELL

The concept of "Biocell" is a variation of the bioreactor landfill approach which entails the operation of a waste cell in different modes to maximize resource and space recovery. During the first phase, the Biocell operates as an anaerobic bioreactor with leachate recirculation and gas extraction for power generation. The second phase is operated as an aerobic bioreactor and converts MSW to a compost-like product. The third phase of operation is mining to recover resources and space, allowing the empty cell to again receive waste and for the cycle to be repeated. This closed loop mode of operation is an attractive alternative to conventional landfilling. Figure 1 shows the various phases of operation of the Biocell.

The Calgary Biocell is a full-scale pilot project that has been implemented to acquire data and demonstrate the applicability of the Biocell concept under extremely cold temperatures. The Biocell is a novel and a sustainable concept (Hettiaratchi et al., 2010). It is expected to continue with the remainder of an anaerobic phase of Biocell and then to anaerobic and mining phases and the monitoring and data gathering will continue.

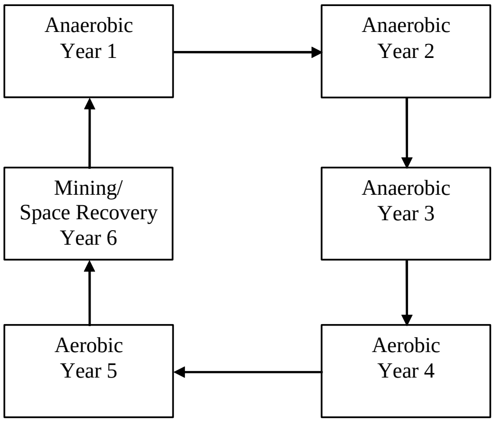

Fig. 1. The Phases of Biocell Operations with Example Durations.

The Calgary Biocell is located within the City of Calgary Shepard landfill site in a low-lying area east of industrial waste cells. The area is relatively on level ground except for the MSW filled areas to the west and south. The cell was designed to accept residential solid waste with feedstock placed in three 5m lifts. There are two 500mm thick intermediate cover layers with a vertical spacing of 5m. These layers are methane oxidizing layers which contained a mixture of compost (25% by volume) and top soil (75% by volume).

Cold winter temperatures can adversely affect the biodegradation in small-scale cells. Therefore, the total waste height of the cell needed to be carefully selected to maintain uninterrupted bio-activity within the biomass even during the winter. In order to achieve this and to provide capacity in a footprint as small as possible, the cell base was placed approximately 5m below grade. The site has a relatively high seasonal groundwater table and the cell lies below groundwater table. The original ground surface approximately coincided with the top level of the first lift. The seasonal groundwater table is approximately 3m below the original ground surface. This produces an inward groundwater gradient reducing the potential for groundwater contamination by leachate.

The leachate collection system consisted of a layer of drainage gravel across the entire base of the cell, a geo-composite on the perimeter slopes, and a drainage gravel trench leading to a leachate collection sump. The granular drainage media extends across the entire base as well as over top of the leachate collection trench. The leachate collection trench consists of a 0.6m deep trench filled with drainage gravel. The leachate trench invert slopes towards the sump and leachate generated within the cell is directed to the leachate sump. The leachate sump is double-lined with a stud-liner, and is installed with a leak detection system.

Waste deposition was limited to residential MSW to improve homogeneity of the material placed in the cell. Another benefit of using residential MSW is that it typically has a high organic content which improves gas production. The deposited waste was neither compacted by earth moving equipment nor used daily cover. The waste in the Biocell was therefore allowed to compact by its own weight. The total amount of waste deposited in the cell was approximately 47,900 tonnes of residential MSW in three lifts of approximately 5m each. The organic content of the residential MSW was approximately 71%, consisting of paper as well as yard and food waste.

Residential MSW was delivered to the Biocell in 20 yd^3 (15.29 m^3) and 25 yd^3 (19.11 m^3) capacity compactor trucks. Approximately of 15,500 tonnes of MSW was accepted for the 1st lift. The 1st intermediate cover was placed in July 2005. From August to mid-November 2005 MSW was then accepted for the 2nd lift. Approximately of 17,052 tonnes of waste was accepted in the 2nd lift. The 2nd intermediate cover was then installed and waste deposition for the 3rd lift commenced at the end of November 2005 and was completed in April 2006. Approximately of 13,312 tonnes of MSW deposited in the 3rd lift with a grand total of 45, 860 tonnes of MSW.

The MSW deposition rate from December 2005 to January 2006 was low compared with the previous months because of downtime in filling to allow for monitoring of emissions from the 2nd intermediate cover. After waste deposition was completed, the vertical gas extraction and liquid injection wells were constructed. The cover was installed in August 2006 and additional MSW was added to achieve the final grade required for the Biocell design. Hence the total MSW deposited in the 3rd lift was approximately 15,352 tonnes and with a grand total of approximately 47,900 tonnes of MSW in the cell.

The Biocell is currently operating as an anaerobic bioreactor. It is expected to continue with the remainder of an anaerobic phase of Biocell and then to anaerobic and mining phases and the monitoring and data gathering will continue. However, currently there is limited knowledge on landfill mining and in order to estimate the best time to initiate landfill mining a comprehensive mathematical model was developed.

PROPOSED MODEL

The numerical model proposed by Hettiarachchi et al., (2007) couples settlements of a Biocell landfill with the generation and dissipation of landfill gases and distribution of moisture by solving the mass balance equation. The heat balance equation is adopted to calculate the temperature increase in the landfill layers due to the biodegradation reaction. The major mechanisms of waste settlement were identified as mechanical compression and biodegradation-induced strain. Mechanical compression was modeled with the help of laboratory simulations. To model the biodegradation-induced settlements, it was assumed that waste degradation obeys the first order kinetic equation. The mass balance of the landfill gas was used to link settlement with gas pressures. Well known Richards equation was used to simulate the distribution of moisture. A computer program was developed to numerically predict the settlements, gas pressures and volumetric moisture contents in a Biocell landfill using landfill geometry and waste properties. In the model, the temperature was assumed as a constant and the settlement and gas generation were calculated based on the mass balance for a period of 3 years. The present study incorporates the heat generated in the landfill system into the existing settlement and gas generation model by incorporating solution of energy balance equation into the numerical model developed by Hettiarachchi et al., (2007).

Heat Generation and Decay Constant: Heat generated in landfills as a result of energy released from a large set of parallel and sequential biochemical reactions, beginning with the hydrolysis of solid substrates and ending with carbon dioxide and methane production. The reactions that occur in a landfill are too numerous and complex. In the existing biological models that are found in the literature, the temperature is considered to be constant and these models are based on a constant value for production and decay of the biomass. The most important part in the biodegradation of the solid substrate in landfills is hydrolysis, which is represented using first order kinetics. Acidogens and methanogens are the only two microbial populations assumed to be present in the simplified landfill ecosystem. The degradation constants are greatly affected by the variation in landfill temperature. The degradation kinetic for the biodegradable component of the biomass is defined by the Arrhenius Law. Arrhenius relationship is the most commonly used equation to determine the microbial bio-kinetics with temperature.

$$K_{hi} = \alpha_{hi} exp - [\frac{E_{hi}}{RT}] \tag{1}$$

Where, K_{hi} is hydrolysis rate of substrate i (day^{-1}), α_{hi} is proportionality constant (day^{-1}) and E_{hi} is activation energy ($kcal\ mol^{-1}$). Temperatures that are usually encountered in sanitary landfills fall in the range of 25–40°C. At higher temperatures above 70°C, the bacterial growth abruptly falls to zero and the gas generation ideally stops. Hence for higher temperatures, the Arrhenius relationship ceases to apply.

The temperature generated in a landfill is a dynamic parameter influenced by the rate of degradation of the landfill material. The degradation constant, based on the Arrhenius equation is temperature dependent. In this study an analogous energy balance for the waste system is included in the numerical model generated by Hettiarachchi et al., (2007). The numerical model proposed in this study couples the temperature, mass and biodegradation kinetics which greatly influence the landfill operation and interdependent on each other. Based on the energy balance, the temperature is generated due to the decay of biomass for each time step. Then the temperature dependent decay constant is recalculated based on the

Arrhenius equation. Then biodegradable mass based on the dynamic decay constants for the different fraction of the biomass is computed at every time step and this procedure is repeated in this study. The temperature generation in the idealized landfill system was determined using the implicit method of numerical simulation. The change in temperature (dT), temperature in each layer for the different time steps were represented in terms of the heat generation and the heat flux terms. A series of simultaneous equations with unknown temperature values were formulated for each time step and solved in MATLAB to generate the temperature profile. The temperature generation, variation in mass and the decay constants were coupled together and calculated for every time step. Arrhenius Equation was used to determine the change in the decay constants with respect to temperature. Thus a coupled approach is put forward to generate more realistic temperature, mass components for the landfill system considered. Finally the numerical results generated were validated with the measured field temperature results obtained from the Calgary Biocell.

BIOCHEMISTRY OF THE DEGRADATION REACTION

Composition of the Biomass: The composition of MSW depends on various factors including climatic conditions, location, waste collection and disposal methods. Many researchers have examined the composition of the MSW. The composition of biomass proposed by Themelis and Ulloa, 2006 is listed in Table 1, where cellulose and hemicellulose represents the major degradable components of MSW. It is also reported that cellulose and hemicellulose fraction of MSW accounts for 91% of its methane potential.

Table 1. Composition of Biomass in MSW
(Themelis and Ulloa, 2006)

Biomass materials	**(%)**
Paper	36.2
Wood	5.8
Yard trimmings	12.1
Food wastes	11.7
Leather cotton and wool	3.7
Total biomass	69.5

Based on the composition of MSW, a composite formula is obtained for the biomass for biochemical analysis, the structural formula for mixed food and green waste is assumed as $C_6H_{9.6}O_{3.5}N_{0.28}S_{0.2}$ and for mixed paper, it is assumed as $C_6H_{9.6}O_{4.6}N_{0.036}S_{0.01.}$ Hence the final molecular structure used in this study is $(C_6H_{10}O_5)_x$ after eliminating N and S, which is closer to cellulose. Thus biomass constitutes 69.6% of total MSW and the composition of cellulosic material is approximately 60%.

Thermodynamics of the Anaerobic Reactions: The net heat generation depends on the heat gain within the landfill mass and the heat losses to the environment. Heat gain results from the heat of reaction (enthalpy) for a large set of parallel and sequential biochemical reactions, beginning with the hydrolysis of solid cellulosic materials to the final step in the production of methane and carbon dioxide. The heat release takes place predominantly during the production of Acetic acid, Propionic acid and Butyric acid. Based on the intermediate reactions the representative reaction for the formation of the bio gas the calorimetric balance for the waste bio-digestion in landfills is given as.

$$C_6H_{12}O_6(S) \rightarrow 3CH_4(g) + 3CO_2(g) \quad \Delta_r H = -145 \text{kJ/mol} \qquad (2)$$

The heat generated is thus directly proportional to the acid formation rate. The net heat produced through the reactions is calculated based on the enthalpy of formation of reactants and the enthalpy of the formation of the products. Based on the above, it is assessed that 1 mole of organic matter (glucose/cellulose) gives 145 kJ/mol of energy. Therefore 180g of organic matter (glucose/cellulose) produces 145 kJ/mol of energy. For 1kg of organic matter (glucose/cellulose) the heat generated is calculated as (145/180)*1000 which is805 kJ/kg of organic matter.

NUMERICAL MODEL

Landfill system: The conceptual model proposed by Hettiarachchi et al**.,** (2007), to compute settlements and gas generation due to both biodegradation and mechanical compression is used in this study. The solids fraction of MSW was divided into four groups: non-degradable, slowly degradable, moderately degradable and rapidly degradable. The waste layers were assumed to have a constant initial height and density at the placement. MSW changes its volume due to the self-weight or load acting on it and the mass loss due to the biodegradation. The rearrangement of MSW after biodegradation produces additional settlement. Thus the total settlement was modeled as a combination of mechanical compression $(\Delta Z)_m$ and biodegradation induced settlement $(\Delta Z)_b$. The landfill geometry is assumed to have 60 layers with 3 lifts each with 20 layers (k layers).The waste layers were assumed to have a constant initial height and density at the placement. The time step of 1 day was assumed for a total time period of 1000 days. The Mass (k,t) incorporates the fractions of materials based on their biodegradability and the thickness of different waste layers were computed based on the compressibility of the waste layers. The hypothetical landfill assumed for the numerical modeling is given in figure 2.

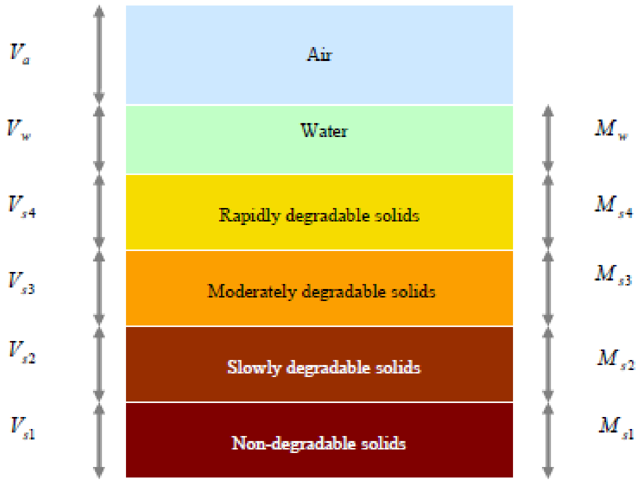

Figure 2: Phase diagram for waste (Hettiarachchi, 2007)

Heat Balance: The heat balance was incorporated into this model to calculate the change in temperature in each layer. The heat balance for the landfill system is established as per equation (3). Where, HI is the heat input in a particular layer and HF is the Heat flux through the layer due to the temperature gradient and HR is the heat due to the biodegradation reaction. The Heat flux is calculated based on the equation (4), where, KT is the thermal conductivity of the material, ΔT is the change in temperature and ΔZ is the height of the layers. Equation (5) is used to calculate the change in the heat capacity of the layers, C, refers to the specific heat capacity of the biomass and ρ is the density of the biomass. HR, Heat generated due to the biodegradation reaction is calculated based on the change in mass in each layer (dM) between 2 time steps, computed as per equation (6) and the heat generated per kg of organic matter, based on the biodegradation reaction and cellulose percentage (eq.7).

$$HI=HF+\Delta HC-HR \qquad (3)$$

$$HF = KT^* (\Delta T/\square Z) \qquad (4)$$

$$\Delta HC= \rho^*C^* \Delta T \qquad (5)$$

$$dM(k,t+1)=M(k,t)-M(k,t+1) \qquad (6)$$

$$HR(k,t)= dM(k,t)^*805000 \qquad (7)$$

Simulation Methodology: For the analysis of the idealized landfill, implicit method of numerical formulation is adopted. The idealized cross-section is shown in figure 3. The landfill system adopted for the present study consists of 60 layers. The initial air temperature is assumed as 290K. The bottom boundary is assumed as a reflection boundary with zero temperature gradient. The temperature at the top layer is assumed as 290K. The heat transfer in the intermediate layers is through conduction. For this particular study, a time period of 1000 time steps is adopted for the simulation. Since the gas generation does not commence at the first time step, the temperature remains a constant. For the subsequent time steps, implicit method of numerical simulation is adopted. The implicit finite difference method involves solving a system of simultaneous linear equations. A system of simultaneous equations with a total of 60 unknown temperature values for each layer is formulated using the energy balance equations.

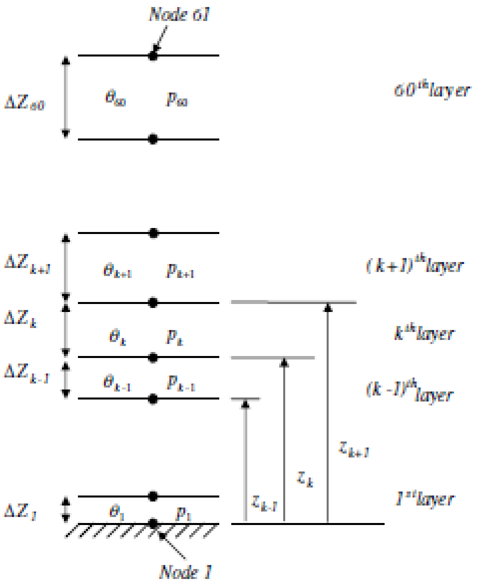

Fig. 3. Idealized landfill cross-section considered in the numerical analysis (Hettiarachchi, 2007).

Formulation of the simultaneous equations: Based on the energy balance equation, the change in temperature dT(k,t) for the landfill layers is expressed in terms of the heat generated HR(k,t), HF (Heat Flux), mass of the biomass and the specific heat capacity of the biomass(Cp). The heat flux is expressed as per the equation (8).

$$HF(k,t)= KT^*(T(k-1,t)-T(k,t))/dZ (k,t) \qquad (8)$$

T(k-1,t), T(k,t) refers to the generated landfill temperatures in the k-1 and k^{th} layers, dZ(k,t) refers to the thickness of the corresponding landfill layer. The unknown temperature in each of the landfill layers is expressed in terms of the change in temperature (dT) and HR. Based on this ‘n’ equations are generated for ‘n’ layers of the landfill system. The simultaneous equations thus generated for each time step is reduced to matrices and the unknown temperature matrix is solved through MATLAB Programming. The equations are reduced to matrices and solved for temperature for the current time step involved.

Matrix formulation: The coefficient matrixes, [A], are given in terms of X and Y, the Temperature vector is represented as [T], and the heat generation vector is represented as [B].

$$[A][T]=[B] \qquad (9)$$

The matrix equation is solved through the MATLAB Programming, and the temperature values are generated for the time steps.

Coupling of Temperature, Mass and Decay constants: The degradation of the biodegradable mass largely depends on the bio-kinetic rate constants. For this particular study, the biomass is divided into four fractions based on the biodegradability. The solids fraction of MSW was divided into four groups: non-degradable, slowly degradable, moderately degradable and rapidly degradable and follows the first order kinetics. The biodegradability of the material increases with the increase in temperature and the decay constant which greatly affects the biodegradation rate, is also directly proportional to the temperature change. In this analysis, a coupled approach is adopted, where the temperature generated in each time step is used to compute the new decay constant for each solid fraction and the corresponding mass is generated based on these updated decay constants. The interdependent temperature, mass and the decay constant depicts a more realistic approach for the landfill analysis. This is accomplished by adopting the Arrhenius relationship (Eq.1).

NUMERICAL RESULTS AND VALIDATION OF THE MODEL

The dynamic variation of the degradable mass with temperature is accounted with the variation of the decay constant through the MATRIX Programming. The temperature generated for the 1000 time steps is shown in Figure 3. The temperature variation at the top layers remains more or less constant at 290K. At the bottom layers, the temperature increases to approximately 318K from 290K. The dynamic temperature distribution and corresponding biomass degradation is more realistic compared to the constant value of the temperature assumed in most of the studies.

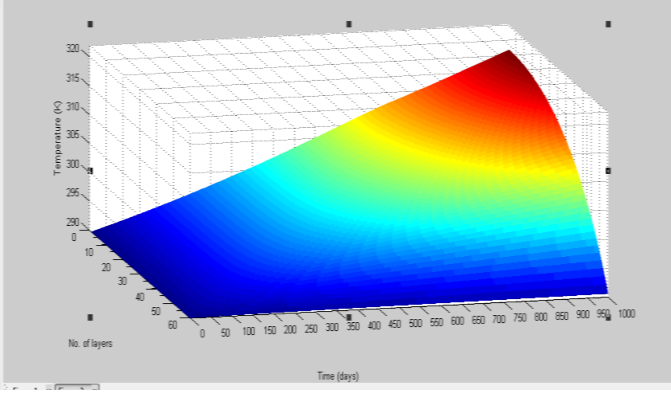

Fig. 4. Temperature generated in each layer for 3 years.

SUMMARY AND CONCLUSIONS

The Calgary Biocell was constructed to acquire data and demonstrate the applicability of the Biocell concept under severe winter temperatures. MSW settlement, leachate recirculation and landfill gas generation of Biocell were monitored over five years. The Biocell is currently operating as a anaerobic bioreactor. It is expected to continue with the remainder of an anaerobic phase of Biocell and then to anaerobic and mining phases and the monitoring and data gathering will continue. In order the facilitate the last phase of Biocell, resource mining, a comprehensive mathematical model was developed by solving both mass balance and energy equations, and temperature dependent decay constants were used to compute the biodegradation of biomass. The numerical model developed can predict temperature and gas generation due to biodegradation by using more realistic decay constants and mass values.

First order decay equation was assumed to model the biodegradation of waste. Conservation of mass as well as energy was maintained. MSW was divided into four groups with different decay constants. The heat generated was coupled with the decay constant through the Arrhenius equation. Implicit method of numerical solution was developed to solve the governing equations. The predicted thermal profile from the numerical simulation depicted a realistic temperature variation with time. Top layer temperatures were around 290K confirming numerical stability. At the bottom layers, a temperature increase of approximately 318K from 290K was observed within 1000 days.

REFERENCES

El-Fadel, M., Khoury, R., Modeling settlement in msw landfills: A critical review.Critical Reviews in Environmental Science and Technology 30 (3), 327–361,(2000).

Hettiarachchi, C.H., Meegoda, J.N., Tavantzis, J., Hettiaratchi, P., Numerical model to predict settlements coupled with landfill gas pressure in bioreactor landfills. Journal of Hazardous Materials B139 (3), 514–522 (2007).

Hettiaratchi, J. P. A., Meegoda, J. N., Hsieh, H. N., and Hunte, C. A. “Sustainable management of household solid waste,” International Journal of Environment and Waste Management, Vol. 6#1-2, pp 96-106, 2010

Themelis, N.J. and P. Ulloa., Methane generation in landfills, Journal of Renewable Energy, 32, 2007, p. 1243-1257;www.aseanenvironment.info/Abstract/41014160.pdf, (2006).