ABSTRACT

MODELING BIODEGRADATION SETTLEMENT OF MUNICIPAL SOLID WASTE (MSW) BASED ON MEASUREMENT OF LANDFILL GAS AND DEGRADABLE SOLIDS IN LEACHATE RECIRCULATED BIOREACTORS

by
Vatsal A. Shah

The purpose of this work is two-fold: 1) to understand the phenomenon of the biodegradation process of municipal solid waste (MSW) in leachate recirculated bioreactors, and 2) to create a realistic predictive model based on this understanding which is capable of supporting a laboratory-to-field relationship for bioreactor landfills. Biodegradation is best described by loss of mass; however, primary researchers have assumed the phenomenon to be purely volume loss and modeled best by mechanical processes using a conservation of energy approach. It is suggested that the phenomenon requires a fundamental understanding of biodegradation process which results in a loss of mass, and therefore an understanding of the conservation of mass must be considered.

It is difficult to measure and predict volume change of a heterogeneous MSW material as well as the change in mass in the field. In the laboratory, under controlled conditions, changes in volume and mass can be determined destructively and a relationship between mass and volume changes can be obtained. Changes in volume in the laboratory are related to the corresponding volumes of gas produced as the MSW degrades. From these measurements, vertical strain (settlement) of MSW landfill and the state of biodegradation as a function of time can be estimated. This is the basis of the research conducted herein. Characteristics curves depicting percent biodegradation and vertical strain as functions of time for a given composition of MSW can be developed.

Four homogenized sample sets, each consisting of composite, readily, moderately, and slowly degradable MSW are prepared and tested in separate bioreactors. These are connected to an electronic gas flow meter, leachate recirculation tubing, and subjected to leachate over a period of approximately 260 days to simulate a landfill environment. Gas production, settlement, and other physical and engineering parameters are measured as these conditions vary. Approximately 72%, 93%, and 62% of the calculated theoretical total gas potentials of 6.23, 9.04, and 8.43 cubic feet per pound waste for composite, readily, and moderately degradable bioreactor sets are collected. From the laboratory program, it is determined that characteristic curves for any composite MSW sample could be developed from the results of the readily, moderately and slowly biodegradable MSW samples using weighted averaging techniques. In a landfill, lifts of MSW, placed at different times, will degrade at different rates and are at different states of biodegradation. A method to determine the average state of biodegradation for such a condition is developed to assist in field validation.

Field validation of the laboratory models based on newly developed characteristic curves is performed on two MSW bioreactor landfills. The first, Cape May County Municipal Utilities Authority bioreactor landfill, exhibits MSW composition similar to the composite waste sample tested in the laboratory. It is determined that the percent biodegradation predicted by the model developed here in is between 3 and 14 percent of the actual field results, and the settlement values predicted by the developed model are in very close agreement with those observed in the field. Similar agreement is obtained using the method for the second, Yolo County landfill located in California, with different MSW composition and environmental factors.

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This dissertation is dedicated to my mother and father, Lata and Atul Shah. They have been a guiding light of inspiration throughout my education, career, and life. Their actions and lessons have molded my character and work ethic, and taught me to believe in preparation over luck. No amount of words will be enough to describe the respect, love, and gratitude I have for them. They have been exemplary parents and friends-- tirelessly offering motivation, guidance, and affection, and introducing my passion to never stop learning, never stop teaching, and never stop moving.

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LIST OF SYMBOLS

α_i	Gas Generation Rate for Specific Waste Type in Durmusoglu et. al Model
a	Parameter Representing Molar Quantity of Carbon in Stoichiometry
A_i	Fraction of MSW Represented by Waste Category in Durmusoglu Model
ASTM	American Society for Testing and Materials
Avg	Average
%B	Percent Biodegradation
$\%B_{avg}$	Average Percent Biodegradation Calculated by Model
$\%B_{converted}$	Mass Expression of Average Percent Biodegradation Considering Density
$\%B_{field}$	Average Percent Biodegradation Calculated from Field Data
$\%B_{volume}$	Volume Expression of Percent Average Percent Biodegradation
B	Biodegradation Ratio
B_1	First Known Value of Percent Biodegradation for Model
B_2	Second Known Value of Percent Biodegradation for Model
b	Parameter Representing Molar Quantity of Hydrogen in Stoichiometry
B_{avg}	Average Biodegradation
B_{mass}	Mass Expression of Biodegradation Ratio
BMP	Biochemical Methane Potential
B_t	Percent of Biodegradation Remaining
BTU	British Thermal Units
BOD	Biochemical Oxygen Demand
°F	Degrees Celsius
C	Chemical Symbol for Carbon

LIST OF SYMBOLS
Continued

c	Parameter Representing Molar Quantity of Oxygen in Stoichiometry
$C_aH_bO_cN_dS_e$	Chemical Expression of Waste for Stoichiometry
(C+H)/L	Ratio of Cellulose (C) + Hemicellulose (H) divided by Lignin (L)
C'_c	Strain Related Compression Index
C'_α	Strain Related Secondary Compression Index
$C_{\alpha\beta}$	Strain Related Tertiary Compression Index
C_β	Strain Related Biodegradation Compression Index
CH_4	Chemical Expression for Methane
CMCMUA	Cape May County Municipal Utilities Authority
CO	Chemical Expression for Carbon Monoxide
CO_2	Chemical Expression for Carbon Dioxide
COD	Chemical Oxygen Demand
d	Parameter Representing Molar Quantity of Nitrogen in Stoichiometry
Deg.	Degradable
D_m	Decomposed Portion of Moderately Degradable Waste
D_r	Decomposed Portion of Readily Degradable Waste
D_s	Decomposed Portion of Slowly Degradable Waste
∂h	Loss of Height
∂W	Loss of Weight of Degradable Substance
dy/dt	Time-rate of Change Expression
Elev.	Elevation

LIST OF SYMBOLS
Continued

ε_z	Vertical Strain
ε_{z1}	Calculated or Known Vertical Strain at Point T_1
ε_{z2}	Calculated or Known Vertical Strain at Time T_2
$\varepsilon_{zapprox.}$	Approximate Average Vertical Strain Calculated From Simplified Model
$\varepsilon_{zaverage}$	Average Vertical Strain Calculated From Model
ε_{zfield}	Vertical Strain Calculated From Field Data
e	Parameter Representing Molar Quantity of Sulfur in Stoichiometry
°F	Degrees Fahrenheit
f	Field to Data Variation Correction Factor by Barlaz
f_1	Laboratory-to-Field Correction Factor
f_2	Theoretical-to-Field Correction Factor
ft^3	Cubic Feet
γ_i	Initial Density of Waste as Placed
γ_f	Final Density of Waste
G	Annual Methane Generation for LandGEM Model
g	Gram
G_T^i	Total Gas Production Potential for Waste Type in Durmusoglu et. al Model
H	Chemical Symbol for Hydrogen
H_2S	Chemical Expression for Hydrogen Sulfide
h	Layer Thickness
h_f	Final Layer Thickness

LIST OF SYMBOLS
Continued

h_i	Initial Layer Thickness
h_{tot}	Thickness of Landfill
I	Descriptive Modifier for Inert Waste
in	Inch
j	Integration Time Increment for LandGEM Model
K	Slope of
k	LandGEM Decay Constant
k_c	Exponential Decay Constant for Composite Waste
k_{lab}	Exponential Decay Constant for Composite Waste Obtained in Laboratory
k_m	Exponential Decay Constant for Moderately Biodegradable Waste
k_n	Decay Constant for Waste Constituent
k_r	Exponential Decay Constant for Readily Biodegradable Waste
k_s	Exponential Decay Constant for Slowly Biodegradable Waste
kg	Kilograms
λ	Greek symbol Lambda, Half-life Decay Constant
λ_c	Half-life Decay Constant for Composite Waste
λ_i*	Proportioned Half-life Decay Constant
λ_{field}	Half-life Decay Constant Observed from Field Data
λ_m	Half-life Decay Constant for Moderately Degradable Waste
λ_m*	Proportioned Half-life Decay Constant for Moderately Degradable Waste
λ_r	Half-life Decay Constant for Readily Degradable Waste

LIST OF SYMBOLS
Continued

λ_r*	Proportioned Half-life Decay Constant for Readily Degradable Waste
λ_s	Half-life Decay Constant for Slowly Degradable Waste
λ_s*	Proportioned Half-life Decay Constant for Slowly Degradable Waste
L	Liter
LandGEM	Acronym for USEPA Landfill Gas Emissions Model
LFG	Landfill Gas
L_o	Estimated Theoretical Potential Methane Generation Capacity of Waste for LandGEM model
lbs	Pounds
ln	Natural Logarithm, Base *e*
log	Logarithm to Base 10
M	Descriptive Modifier for Moderately Degradable Waste
m	Meters
m^3	Cubic Meters
m.c.	Moisture Content
M_{CH4}	Reaction Mass of Methane in Stoichiometric Expression
M_{CO2}	Reaction Mass of Carbon Dioxide in Stoichiometric Expression
M_i	Mass of Solid Waste Disposed in the i^{th} Year for use in LandGEM model
mol	Molar Quantity
MSW	Municipal Solid Waste
N	Chemical Symbol for Nitrogen
N_2	Chemical Expression for Nitrogen Gas

LIST OF SYMBOLS
Continued

ND	Non-decomposable
NH_3	Chemical Expression for Ammonia
n_m	Proportion of Moderately Degradable Waste from Waste Composition
n_r	Proportion of Readily Degradable Waste from Waste Composition
n_s	Proportion of Slowly Degradable Waste from Waste Composition
O	Chemical Symbol for Oxygen
O_2	Chemical Expression for Oxygen Gas
P_{CH4}	Percentage of Methane Gas in Landfill Gas
Q_{CO2}	Quantity of Carbon Dioxide Gas from LandGEM Model
Q_{CH4}	Quantity of Methane Gas from LandGEM Model
Q_{total}	Quantity of Total Landfill Gas from LandGEM Model
R	Inert Weight Ratio
RPD	Relative Percent Deviation
S	Chemical Symbol for Sulfur
s	Descriptive Modifier for Slowly Degradable Waste
sccm	Standard Cubic Centimeters per Minute
$Secant_{\beta}$	Secant Modulus of Biodegradation
t	Time (measured in units of seconds, minutes, or years)
t_{50}	Half-life time
t_{95}	Time to 95% Decomposition
t/t_{50}	Normalized Time Ratio of Time Divided by Half-life

LIST OF SYMBOLS
Continued

T_1	Time Corresponding to First Known Strain or Percent Biodegradation
t_1	Time for Maximum Gas Production
T_2	Time Corresponding to Second Known Strain or Percent Biodegradation
t_2	Time for Readily Degradable Region of Gas Production
t_3	Time for Moderately Degradable Region of Gas Production
T_{ab}	Normalized t_{ab} with t_{50}
t_{ab}	Time Between First and Second Known Strain or Percent Biodegradation
t_f	Final Time at Period of Interest
t_i	Initial Time
tsf	Tons Per Square Foot
USEPA	United States Environmental Protection Agency
V_1	Volume Measured at End of Time of Interest
$V_{cumulative}$	Cumulative Volume of Gas Collected up to Time of Interest
V_d	Volume of Material Decomposed
V_{inert}	Volume of Inert Fraction (Interchangable with V_n)
V_n	Volume Non-degradable Waste Fraction
V_m	Volume Moderately Degradable Waste Fraction
V_f	Final Volume
V_o	Initial Volume
$V_{organic}$	Volume of Organic Portion
V'_o	Initial Cumulative Gas Production per Cubic Foot of Waste from Year 0-10 for Raghu and Gausconi Model

LIST OF SYMBOLS
Continued

$V_{phase\ 1}$	Initial Phase of Gas Production $\geq$ 10 Years for Raghu and Gausconi Model
$V_{phase\ 2}$	Final Phase of Gas Production < 10 Years for Raghu and Gausconi Model
$V_{theoretical}$	Total Theoretical Gas Potential
V_{total}	Cumulative Gas Production for Raghu and Gausconi Model
V_r	Volume Readily Degradable Waste Fraction
V_s	Volume Slowly Degradable Waste Fraction
VS	Volatile Solids
V_t	Total Volume
V_{CH4}	Volume of Methane Gas
V_{CO2}	Volume of Carbon Dioxide Gas
w/w	Weight per Weight Percent (Solution)
W_i	Weight of Specific Waste Constituent
W_{CH4}	Weight of Methane Gas in Stoichiometric Expression
W_{CO2}	Weight of Carbon Dioxide Gas in Stoichiometric Expression
$W_{degradable}$	Weight of Degradable Portion of Waste
W_{dry}	Dry Weight of Waste
W_{final}	Final Weight of Waste
W_i	Weight of Inert Portion of Waste
$W_{initial}$	Initial Weight of Waste
W_m	Weight of Moderately Degradable Portion of Waste
W_n	Weight of Non-degradable Portion of Waste

LIST OF SYMBOLS
Continued

W_r	Weight of Readily Degradable Portion of Waste
W_s	Weight of Slowly Degradable Portion of Waste
W_{tot}	Total Weight of Waste Inclusive of All Degradable and Inert Portions
W_{water}	Weight of Water
W_{org}	Dry Weight of Organic Portion of Waste
y_1	Practical Maximum Gas Collectable from Straight-line Portion
y'_{max}	Practical Maximum Gas Collectable from Exponential Curve Portion
$y_{max\text{-}actual}$	Total Practical Maximum Gas Collectable
$year^{-1}$	Inverse Fraction of Year Time

CHAPTER 1

INTRODUCTION

1.1 Objective

This dissertation presents the general outline of a hypothesis developed by the writer and the results of a laboratory program conducted in support of this hypothesis. All laboratory testing was generally conducted in accordance with the document titled "Proposal for Dissertation" submitted in October 2012 and revised based on subsequent discussions with the doctoral committee.

1.2 Hypothesis

The full nature and purpose of this research is to develop an understanding of the biodegradation process to better define the mechanism of settlement as it relates to volume of gas and loss of biodegradable solids. The work will attempt to identify the state of biodegradation of municipal solid waste (MSW). The work also attempts to model the magnitude and rate of gas production and biodegradation settlement associated with MSW landfills typical of New Jersey so that a relationship can be created to relate laboratory conditions of samples to field conditions.

Although the work proposed is regional in nature, by completion of the work, a method will be developed such that it can be repeated to predict the characteristics of any region and composition desired. The work will allow the creation of a composite, characteristic curve based on knowledge of the proportion of readily, moderately, and slowly degradable waste comprising a sample of mixed MSW.

It is being theorized in this work that the ratio of the volume of gas produced up to time “t” against the total of gas the landfill can produce, along with a measurement of the remaining percent organic solids of the waste, can relate to the percent biodegradation of the waste material. By knowing the theoretical gas potential and initial composition of the waste, the author hypothesizes that the amount biodegraded and remaining to biodegrade can be determined through records of gas collection, by testing for percent organic solids, or field-measurement of settlement at the operational landfill taken at two or more discrete time intervals. Then, using characteristic curves developed by this work for the readily, moderately, and slowly degradable waste and proportioning to create a composite curve, the strain and time remaining to practical biodegradation can be estimated.

While a gas production model with a single first-order decay rate may be used as recommended by various authors (Lifrieri 2010, Barlaz et. al 2010, Tolaymat et. al 2010, and Durmusoglu et al. 2005), it is the proposer’s opinion that the single decay constant used in gas production modeling is not applicable in modeling the biodegradation of MSW. This is since the waste is comprised of varying components of constituents with different levels of biodegradability. Therefore, it is proposed to separate this single, weighted decay constant with three separate constants can be used for the individual portions of readily, moderately, and slowly biodegradable wastes, respectively.

The author hypothesized a technique to estimate the decay rate of any waste composition using separate bioreactors of each bioavailable waste type, and created from which the individual decay constants for this composite waste to be estimated. Then, by knowing the proportions of each of these waste types in a composite waste sample, a weighted decay constant for any waste can be estimated.

Biodegradation is best described by loss of mass; however, primary researchers have assumed the phenomenon to be purely volume loss and modeled best by mechanical processes using a conservation of energy approach. It is the opinion of the author that the phenomenon necessitates a fundamental understanding of biodegradation process which results in a loss of mass, and therefore an understanding of the conservation of mass must be considered. The author hypothesizes that it is difficult to measure and predict volume change of a heterogenous material. This property can be measured by quantity of gas produced and recovered, or strain; however both are indirect measures. Conversely, mass is a directly measureable property of the material and can more accurately predict volume changes. It is the author's opinion that, by understanding both properties, a better relationship can be suggested to model the biodegradation process.

The author originally proposed using (C+H)/L as an indicator to relate the state of decomposition; however, it was determined to have shortcomings due to erroneous readings of the lignin fraction caused by synthetic materials such as plastic, rubbers, and textiles. While it is proposed that these materials may be removed from future samples prior to analyses, these results would not be directly comparable to other previous tests conducted on waste material as the proportion is not normalized for each sample and would change with respect to time. Additional discussion on this matter is provided in Chapter 5. The author subsequently suggests that decomposition settlement of MSW will be governed by the relative amount of this biomass material that is present in the waste by measure of percent organic solids.

1.3 Statement of Problem

The purpose of this work was two-fold: 1) to understand the phenomenon of the biodegradation process, and 2) to create a realistic predictive model for MSW landfill settlement based on this understanding which is capable of supporting a laboratory-to-field relationship.

Mass loss, volume, and strain in MSW occur due to degradation of MSW. However, the mechanics of these occurrences has never been fully understood. Understanding the rate and magnitude of settlement, and likewise the state of decomposition, has been a topic of interest for researchers and practitioners. Many related fields, including chemical, environmental, civil, and other branches have discussed and attempted to create relationships to support planning, construction, and reclamation work for MSW landfills.

By determining the magnitude of this settlement, as well as time effects, engineers are able to design closure, grading, and piping as well as potential foundations and structures for any possible future redevelopment of such sites to accommodate subsequent movements of waste. Practically, many agencies in the United States and internationally establish regulations which require landfill operators and agencies to monitor, maintain, and leave funds in escrow for decades after closure of the landfill. Such funds are to be utilized for these maintenance activities until the landfill has reached end of substantial degradation. The practical use of the model proposed in this study is to estimate the state of biodegradation of the waste material at any time within the landfill, and predict the time required for substantial settlement to occur in a landfill.

Understanding the relationship between biodegradation on the waste and gas production modeling, taking into account the waste composition proportions, will assist in correlating laboratory conditions to in-situ conditions and determine the percent of biodegradation remaining to occur at any required time. By obtaining a better time-settlement relationship, the author suggests that the closure period can be more accurately determined and may likely be shortened than what the current practices call for. This will reduce the cost of maintenance of landfill during closure and also make the redevelopment of such sites more viable and feasible.

It should be noted that most of the existing models for landfill settlement are empirical and thus attempt to estimate the settlement by a best-fit assumption over a data set which includes a wide variation of landfill types, composition, thicknesses, and environments. The vast majority of them do not even consider biodegradation-related effects and the few that do (Edgars et.al 1992, Wall and Zeiss 1995, Gabr and Valero 1995, Park and Lee 1997, Coumoulous and Koryalos 1999, Oweis 2006) account for it using another empirical coefficient factor for the secondary settlement.

In a similar regard, these settlement models may be outdated since revised operating strategies for landfills as bioreactors introduce new variables such as leachate recirculation which increase the rate of settlement and production of gas. Existing models are inefficient since they rarely separate the biodegradation-related component from the overall secondary settlement and are focused more on estimating the magnitude rather than the rate of settlement. Some of the later models such as those developed by Hossain et.al (2003) involve specialized chemical testing and long term geotechnical testing. Others are based on complex theoretical models (Liu et. al 2006, Hettiarachchi et. al 2008, Hettiarachchi et. al 2006). So there is a need to develop a simple realistic model that is easy to apply and which requires less testing and theoretical sophistication than those in the existing models.

It is the author's opinion that, the best way to model degradation of MSW is to perform laboratory studies and analyze them with models that account for the mechanism of biodegradation such as those by Disbrow (1988), Raghu and Arntz (1993), Raghu and Gausconi (2002), and Lifrieri (2010). Additionally, a landfill in United States may have much different types and percentages of waste than one in Europe. In existing models for landfill settlement and gas production, the variable of landfill composition has not been accounted for. The author has attempted to confront this issue by the use of a several separated sets of readily, moderately, and slowly-biodegradable wastes and collecting gas production and state of decomposition data from them. Based on the proportions of each of these materials of the landfill composition in question, a composite gas production curve can be created to model the theoretical gas production of a similar representative MSW sample. Details of the model are described in Chapter 6. Applications of the model to case studies are presented in Chapter 7.

CHAPTER 2

A REVIEW OF THE BIODEGRADATION PROCESS

2.1 Background Information

As part of the objective of this work is to form an understanding of the biodegradation process, the author has reviewed existing literature and has provided a summary of the biodegradation process herein.

It is generally accepted that a solid waste landfills can be characterized as a bioreactor system where solid waste and water are major inputs, and landfill gas and leachate are principal outputs (Tchobanglous 1993). As such, material stored the within landfill consists of waste material in variable states of decomposition, along with inert and inorganic material. As the decomposable fraction continues to degrade through a combination of biological, chemical, and physical processes, principal gases including methane (CH_4), carbon dioxide (CO_2), ammonia (NH_3), Nitrogen (N_2), oxygen (O_2), hydrogen sulfide (H_2S), and carbon monoxide (CO) are generated. During biological decomposition carbonaceous components are converted into cellular and partially decomposed matter and gaseous end products, while chemical decomposition is completed through hydrolysis, dissolution-precipitation, sorption-desorption, and ion exchange of the wastes' chemical components. Physical decomposition includes the process of flushing, rinsing, and breakdown action of water movement through the waste material as a result of pressure gradients (Ham 1979).

As waste materials degrade, it is of functional and commercial importance to understand the rate and total quantity of gas which will be produced. This rate and quantity are considered such that gas collection systems can be designed to prevent landfill gas entering the atmosphere, to prevent migration through surrounding soils and waste to damage landfill cover and liner systems, as well as economics planning for landfill gas recovery systems for capture and energy production as biofuel. The total quantity of gas generated is directly proportional to the fraction of organic waste contained within the fill (Day 1994, Manley 1992, Ham and Barlaz 1989). However, it is recognized that the rates of decomposition will vary with a portion of waste degrading rapidly, some portion moderately, and some over an extended period of time. The rate at which gas is produced is then predominantly a function of the type of waste, for example food waste in comparison to textiles or plastic. The overall rate, however, is affected by a variety of factors including moisture, particle size, pH, temperature, composition, addition and availability of nutrients, temperature, and rates of gas extraction (Barlaz et al. 1990, Rice 1989, Pohland 1986, Farquhar and Rovers 1973).

As moisture content is increased, it has been shown that the percentage of methane generated is increased. This indicates that the flow of moisture into and through a landfill likely stimulate microbial activity by promoting more efficient contact between microorganisms, available nutrients, and substrates (Barlaz et al. 1990). It is further shown by the functional approach of traditional landfills in comparison to bioreactor landfills. In traditional landfills, the readily and moderately decomposition fractions of the waste typically require 30 to 50 years or more to reach degradable waste half-life as inferred by USEPA (2003). Conversely, bioreactor landfills promote the recirculation of moisture (leachate) to enhance the microbiological process to transform and stabilize these fractions within a shorter period of time, typically 8 to 15 years to reach half-life for degradable waste as inferred by Barlaz et. al (2008) and USEPA (2003).

2.2 Processes and Phases of Biodegradation

The generation of principal landfill gases has been believed to occur in four generally sequential phases. During the progression of each phase the composition of landfill gas produced changes with time. Also, as additional waste is placed throughout the operational life of a landfill, the landfill may be undergoing several phases of decomposition in different placed layers which will result in varying phases of decomposition of the waste. The four phases consist of an initial adjustment phase, transition phase, acid phase, and methane fermentation phase. The general concentrations of principal gases with respect to time of decomposition have been depicted in Figure 2.1. Gas production and time rate of landfill gas production is described further in Chapter 3.

During Phase I (initial adjustment phase), biodegradable constituents undergo microbial decomposition soon after they are placed into the landfill. During this phase biological decomposition occurs under an aerobic condition as a certain amount of air is trapped within the landfill and oxygen-consuming bacteria break down long molecular chains of complex carbohydrates, proteins, and lipids that comprise organic waste. The main byproduct of this phase is carbon dioxide along with nitrogen; however, nitrogen rapidly declines once available oxygen is depleted. The gas produced is characterized by relatively high temperatures (up to 130 ^{o}F)(Rice 1989) Generally, this phase can last for days or several months and is proportional to the oxygen level when first placed.

The phase is also related to density, as the amount of entrained oxygen is also a function of reduced air voids with more compact waste and more voids and potential for oxygen in loose waste.

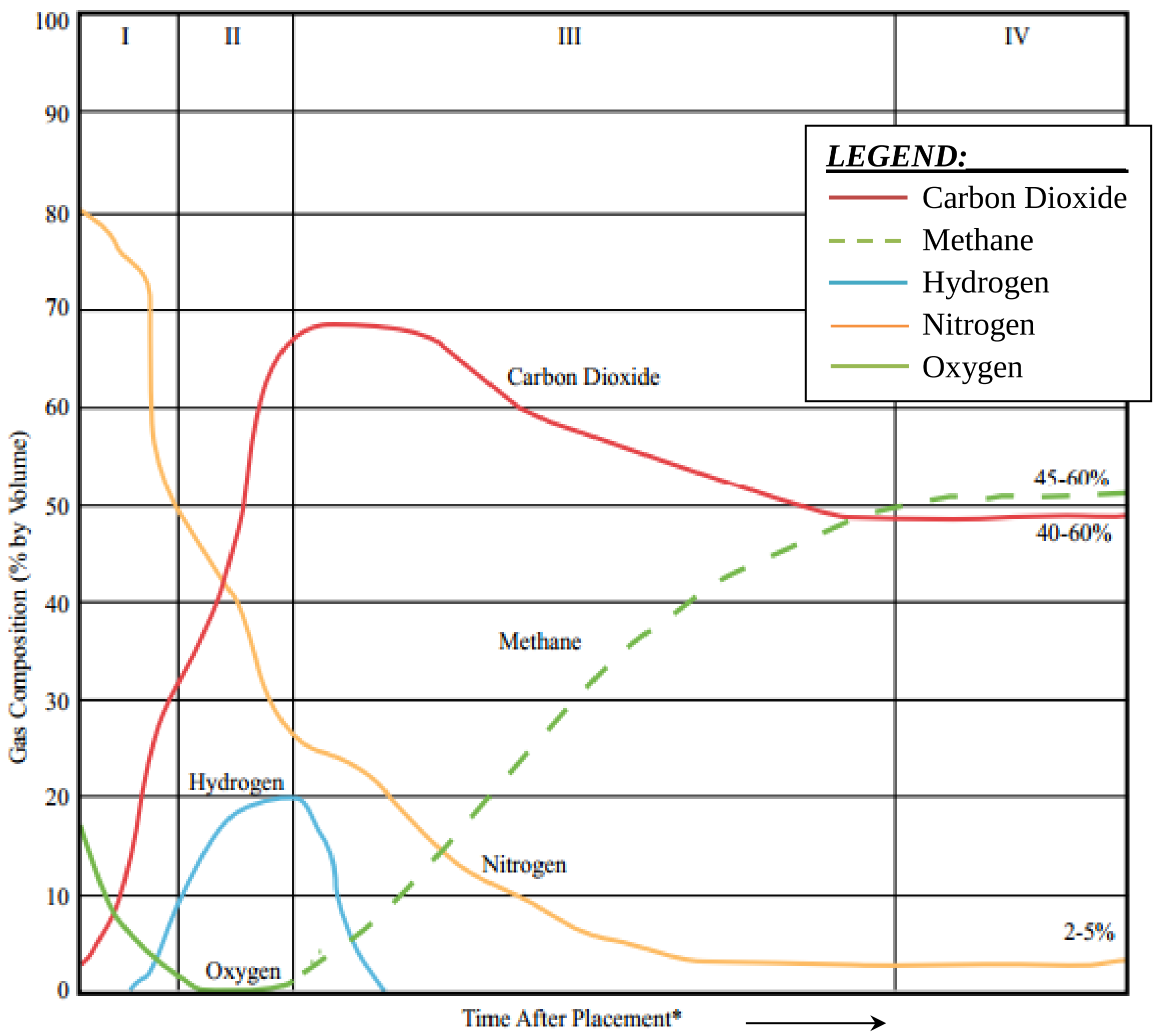

Figure 2.1 Production and Concentrations of Principal Landfill Gases by Phase During Decomposition
Source: ATSDR (2008)

During the next phase (Phase II), a transition generally occurs as oxygen is rapidly depleted and anaerobic conditions dominate. Bacteria convert compounds created by aerobic bacteria into acetic, lactic, and formic acids and alcohols such as methanol and ethanol and subsequently causing the landfill to become highly acidic. The mixture of acid and moisture cause certain nutrients to dissolve, allowing nitrogen and phosphorus to become bioavailable (MDEP 2007). The principal landfill gas byproducts of this phase are carbon dioxide and hydrogen. The onset of this phase can be further characterized by the initial drop of leachate pH due to the presence of organic acids and the effect of elevated concentrations of carbon dioxide in the landfill (Tchobanoglous 1993). It should be noted that, if the portion of landfill that is undergoing this phase is disrupted allowing oxygen to be re-introduced into the landfill, the microbial process will revert back to an aerobic condition (Phase I). Up to 20 percent biodegradable solids loss has been observed to occur during this phase (Palmisano and Barlaz 1996).

The third phase (Phase III), typically considered the unsteady phase, acid phase, or accelerated methane phase, occurs as the microbial activity initiated by Phase II accelerates with the production of significant amounts of organic acids (Tchobanoglous 1993, ATSDR 2008). Microbial activity accelerates when certain classes of anaerobic bacteria consume these organic and form acetate. Through this process, the landfill environment (pH) tends to become more neutral and methane-producing bacteria begin to establish themselves. A three step process occurs throughout this phase including hydrolysis, acidogenesis, and dissolution of organic acids (Palmisano and Barlaz 1996). During hydrolysis higher molecular mass compounds such as lipics, proteins, and polysaccharides are transformed into compounds suitable for microorganisms as a source of energy and cell carbon. Following hydrolysis, acidogenesis occurs which involves the conversion of these transformed compounds into lower mass intermediate compounds such as acetic, fulvic, and other organic acids. Dissolution occurs following both processes as the pH of the leachate drops in the presence of organic acids, and biochemical oxygen demand (BOD), chemical oxygen demand (COD), and conductivity increase significantly. It should be noted that many essential nutrients are removed in the leachate during this Phase. If leachate is not recycled, essential nutrients are lost from the system (Tchobanoglous 1993). It is therefore important that leachate is allowed to circulate otherwise the conversion products and acids produced during this phase will remain in the system and not allow a progression to the next phase (methane fermentation). Understanding of the importance of leachate during this phase has helped support the basis for evolution of the bioreactor landfill concept.

During the fourth phase (Phase IV), known as methane fermentation or decelerated methane phase, methanogenic and strictly anaerobic microorganisms convert previously-produced acetic acid to methane and carbon dioxide. As acids become converted to methane and carbon dioxide, the pH within the landfill environment will rise to a more neutral value and the BOD, COD, and conductivity of leachate will be reduced. Up to 50 percent biodegradable solids loss has been observed to occur during this phase (Palmisano and Barlaz 1996). In traditional landfills, gas is produced at a measurable rate for approximately 30 years; however, gas may continue to be emitted for 100 or more years after the waste is placed in the landfill based on the availability of leachate, temperature, and other environmental factors (Lifrieri 2010, Crawford and Smith 1985).

A fifth phase, the maturation phase, is suggested by several authors to occur at the end of the methane fermentation stage and after any readily and moderately available biodegradable organic material has been converted to methane and carbon dioxide in previous phases (Tchobanglous 1993, Pohland 1987). The rate of landfill gas generation decreases substantially as most available nutrients have been removed by leachate, and the majority of the remaining degradable fraction are slowly biodegradable or products of humic and fulvic acid, which are biologically difficult to process by microorganisms. The re-introduction of nitrogen and oxygen as components of landfill gas may occur as a result of the closure.

Figure 2.2 illustrates the proportional loss of degradable mass as each phase of the biological process progresses. However, some quantity of degradable mass will remain in the landfill as the capping of the landfill may prohibit future introduction of moisture to create leachate or the waste is inaccessible to leachate and moisture due to blocked flow paths.

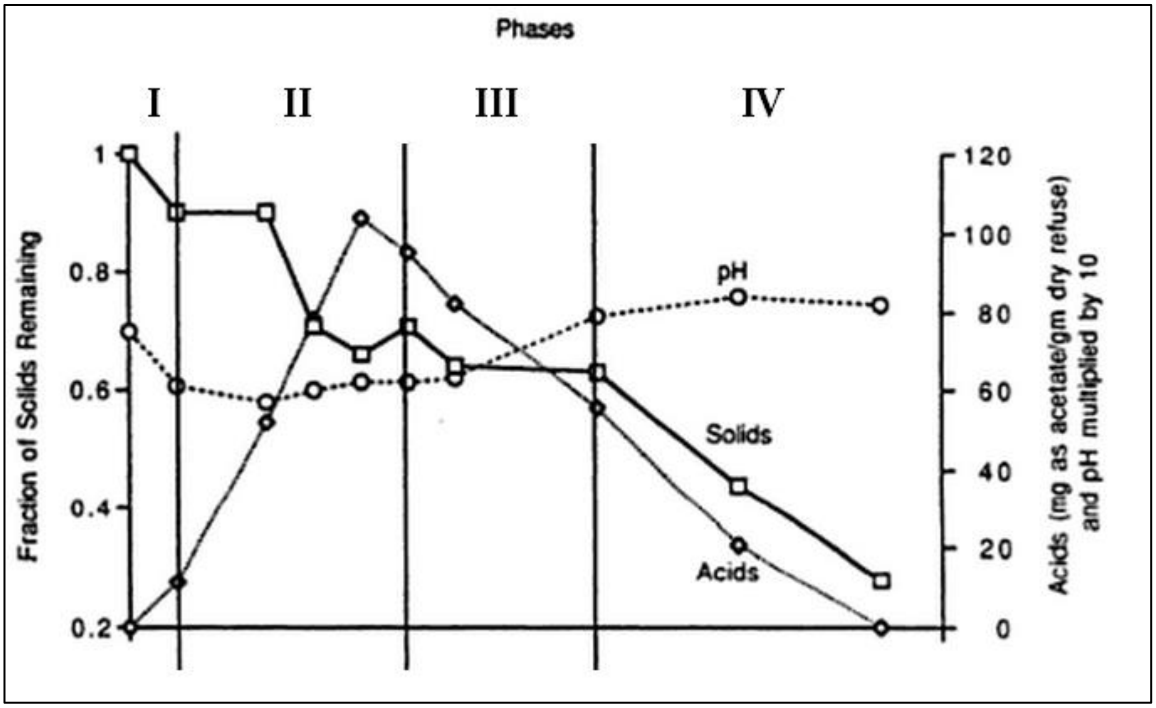

Figure 2.2 Cumulative Loss of Biodegradable Solids as a Function of Phase
Source: Microbiology of Solid Waste, Palmisano and Barlaz (1996), p. 40

While the lifecycle for the first three phases to occur and time to reach the half-life of degradable waste is generally 30 years for traditional landfills and between 8 and 15 years for bioreactor landfills, the time duration is highly sensitive to a variety of factors including moisture content of waste, compaction of placed waste, availability of nutrients, and heterogeneity of waste composition. For example, if a waste is poorly placed and compacted, more oxygen may be available which will create a lag in the transition to anaerobic conditions. Conversely if the waste is well-compacted, methane production may begin earlier; however the denser compaction may make the movement of leachate which is essential for nutrient transport more difficult. Moderate compaction, among other factors such as temperature, cover soil, leachate recirculation, and others, is preferred to promote decomposition (Lifrieri et. al 2006, Tchobanoglous 1993).

Due to the fact that refuse is placed in a landfill at different times and consists of different types of solid waste, the various phases of degradation may be occurring simultaneously within different layers of waste.

The biodegradation process is a time-dependent phenomenon. It is recognized that the onset of gas production does not occur instantaneous after waste placement. It requires some time for the reaction to initiate, and also time is required for the generated gas to travel from the generation to the collection to the point of collection. Additionally, there takes time for gas to be generated in sufficient quantity where it becomes measurable. Therefore, it is observed through this work and by others that there exists a time lag between the fill placement and measurement of gas production.

2.3 Discussion on Traditional, Leachate Recirculation, and Bioreactor Landfills

The currently-practiced concept of landfilling consists of placing waste and creating a “dry tomb” once closed. This concept is promoted to preclude the introduction of water and precipitation which would generate additional leachate, which would require collection and cause biodegradation to continue. It is also driven by the preference of industry to reduce the treatment of leachate, contaminants transported by flushing through the waste, and exposure to environment. As early as 1970, it was suggested that adding nutrients, inoculum, buffers, and recirculating landfill leachate the process of biodegradation could be accelerated (Pohland 1975).

In more recent years, a movement has gravitated towards attempting to design and manage landfills in a controlled manner to deliberately introduce liquids such as leachate, stormwater, sludge, and others which promote degradation. As owners, operators, and designers studied the introduction of liquids it was determined that waste with up to 40 percent moisture content would support biodegradation and designated these landfills as leachate recirculation landfills. Further, above 40 percent moisture content it was determined enhanced biodegradation of the waste was promoted. These landfills were designated as bioreactor landfills (USEPA 2003). Generally moisture content above 60 percent is observed as an upper limit as the waste becomes “soft”, and geotechnical performance of the landfill with respect to slope and liner stability becomes problematic (USEPA 2006). Traditional landfill waste was observed to have an average moisture content of 25 percent by weight (Tchobanoglous 1993).

It should be noted that the introduction of liquids into the landfill causes significant increases in waste decay rates; however, the total quantity of landfill gas should not change, only the time rate at which is produced (USEPA 2010). Similarly the operation of a bioreactor landfill will not affect the sequence of the degradation phases, only the duration of each phase (Pohland and Kim 2003, Reinhart and Townsend 1998, Pohland and Al-Yousfi 1994). Studies conducted on a field-scale leachate recirculation landfill corroborated the potential for higher methane yields, and consequently increased rate of settlement, when compared to a traditional, control landfill during the same reference timeframe (Metha et al. 2002) Additional discussion on rate effects of bioreactor landfills is forthcoming in Chapters 3, 6, and 7.

Along with the benefits of biological stabilization and decomposition in years instead of decades, it is anticipated that bioreactor landfill will become more frequent as it also provides measureable incentives to landfill owners and operators. As the waste decomposes at an accelerated rate, 15 to 30 percent gains of landfill airspace have been observed as a result of increased density and settlement (USEPA 2003). In addition to reduced leachate disposal costs, reduced post-closure care period, and improvement in gas collection efficiency and conversion rates, indicate a shift toward this method.

2.4 Relationship of Biodegradation and Compressibility

Although landfill settlement can occur in the soil and void spaces in the landfill, the majority of settlement occurs in the waste mass as it decomposes. The majority of authors postulate that MSW landfill settlement occurs in three distinct phases: immediate compression (caused by self-weight or compactive efforts); primary settlement (caused by dissipation of pore water pressure or gas); and secondary settlement (caused by biodegradation and creep)(Bareither et. al 2012, Zekkos 2012, Lifrieri 2010, El Fadel and Al-Rashed 1998, Wall and Zeiss 1995, Bjorngaard and Edgers 1990, Edil et. al 1990).

However, it is the opinion of the author that the biodegradation (biological) and creep (mechanical) processes of the secondary settlement are actually two distinct phases. Therefore, five phases (immediate compression, primary compression, inorganic secondary compression, biodegradation, and tertiary creep) comprise the overall settlement of MSW landfills. Figure 2.3 outlines these phases.

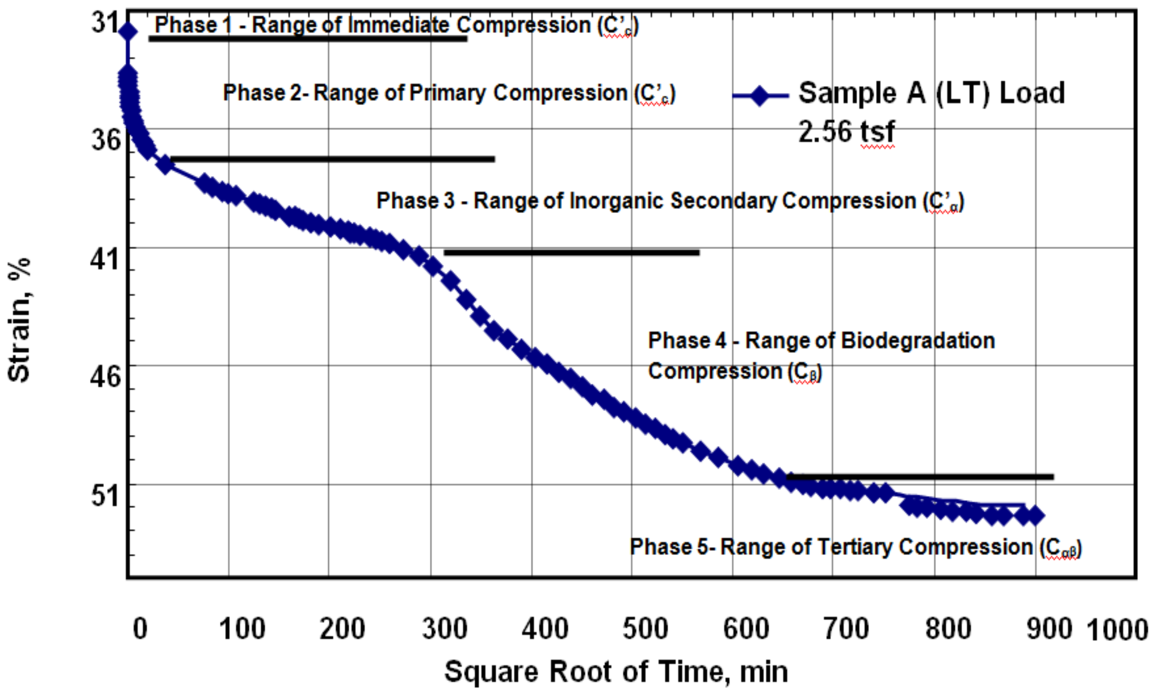

Figure 2.3 Idealized Long-term Settlement Curve
Source: Lifrieri (2010)

Immediate compression, although difficult to see in the above graph, occurs rapidly and is the result of compaction efforts and self-weight when the MSW material is initially placed at the landfill site. Because the waste is generally delivered in a loose state, the material skeleton is highly permeable which allows mechanical rearrangement to occur rapidly. The time for this phase to complete is typically within hours of placement in field conditions to as rapid as 4 minutes in laboratory conditions (Lifrieri 2010). A typical strain versus time (in logarithmic scale) curve is presented in Figure 2.4.

The primary compression (until time t_1, as shown in Figure 2.4) is approximated using Terzaghi's theory of conventional soil mechanics for consolidation (where the slope of the line is C'_c) with the time of the end of this mechanism being determined by methods similar to Bareither et.al 2012. The C'_c coefficient in this case is dependent on several variables, such as in-place density, level of compaction, and initial state of biodegradation (measured by the [C+H]/L ratio) of the placed waste (a waste that has been placed after a large portion of degradation has occurred will act more soil-like than a freshly placed waste)(Hossain et. al 2003). This phase is presumed to occur rapidly (within 12 to 60 days in the field (Bareither et.al 2012) and within approximately 15 hours in the laboratory (Lifrieri 2010).

The third phase (or inorganic secondary settlement) can be approximated using a concept similar to Terzaghi's for inorganic creep rate (defined as C'_{α}) and is the interval at which gas production and biodegradation have yet to develop. This variable is based on the skeletal structure of the material and is generally independent of the state of decomposition of the waste. It is primarily a function of time dependent strain under a load.

The fourth, biodegradation-related phase is time dependent and based on the degree of decomposition of the waste. This state of decomposition can be measured by the percent biodegradation of the waste or also the ratio of volume of gas produced by degradation and total volume. The coefficient of biodegradation (C_{β}) is a property of the percent biodegradation versus time curve. The time for the completion of this phase would be determined based on the onset of gas production until the gas production nears an asymptotic value.

Finally the fifth phase, tertiary compression (or residual creep), may be approximated using classic soil mechanics models since the waste has attained a state of degradation (beyond which the rate of change of biodegradation becomes nearly constant) where the material behaves in an inorganic soil-like manner. This creep can continue much after landfill closure to periods of time exceeding 30 years (Zekkos 2012).

It should be noted that, although all five phases are shown with each occurring at discrete time segments, they are not truly independent and actually all occur simultaneously. Biodegradation is a slight exception to this; however after gas production has begun to start it continues to act simultaneously with the other phases. During each phase, all other phases are occurring however one type of mechanism may be dominant at one time while the others are passive until another interval.

To predict the long term settlement using a single compression index to describe the inorganic and organic compressibility of the waste material, one author (Lifrieri 2010) proposed the concept of the biodegradation secant modulus compression index, $Secant_{\beta}$. When the strain versus time (in log scale) of the waste material is plotted over a complete cycle of time covering the time $C'_{\alpha}$and C_{β} occur, this modulus can be determined. The modulus can then be used to predict future tertiary settlement for several log cycles until the waste has stopped compressing (t_f).

The five phases of biodegradation are independent of the phases observed during compression testing. More discussion will provided in Chapter 5 during the presentation and review of consolidation testing results.

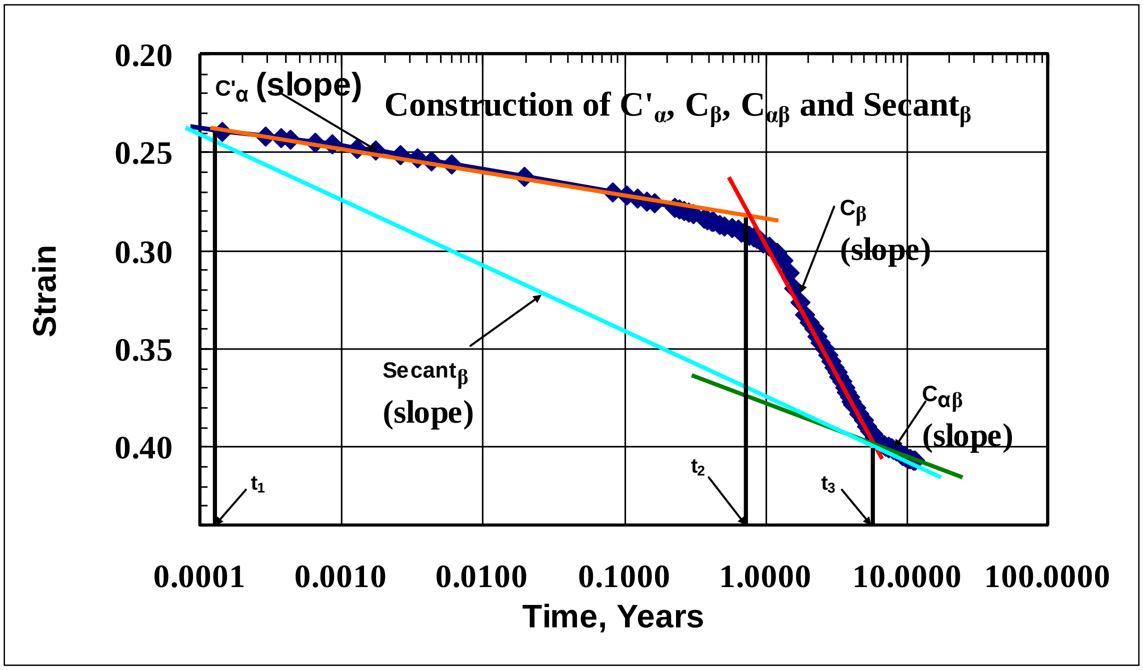

Figure 2.4 Construction of Compression Indices
Source: Lifrieri (2010)

Many authors have attempted to define the effect of the total secondary compression (lumping both inorganic and biodegradation phases together) based on rheologic models, power creep models, and other empirical models. In 1977, Rao et.al developed a model to predict the total settlement of the waste as a function of load neglecting the time effect on the settlement. While the method has some degree of accuracy, it is not very popular as the waste settlement continues for a very long period of time due to the biodegradability of the waste.

A rheological model by Gibson and Lo (1961) was created for the evaluation of long-term secondary compression of peat-type soils which was further refined by Edil et.al (1990) to represent the one-dimensional compression of refuse fill. While peat exhibits a similar biodegradation phase, it cannot account for the heterogeneity of MSW material. Edil et.al (1990) also refined a power creep model for time dependent settlement production under constant stress which has been used extensively for transient creep behavior of many engineering materials, however it relies on reference compressibility coefficients and compression rate coefficient which show no discernible pattern with respect to the placement conditions of the refuse.

Ling et.al (1998) combined the logarithmic function and power function to propose a new empirical relationship for the settlement prediction of the waste. A hyperbolic model was also created. However, at large values of time (practically at the end of landfill closure), the model gives negative settlement which may indicate that the landfill expands which is physically impossible. A logarithmic function model by Yen and Scanlon (1975) was also attempted to determine the settlement and similar attempts were made by Bjorngaard and Edgers (1990) to compile data from traditional landfills in an attempt to create an empirical model for landfill settlement based on this data set.

Bjorngaard and Edgers (1990), Mitchell et.al (1995), and Wall and Zeiss (1995) all created models similar to Terzaghi's classical consolidation model approach for prediction of overall waste settlement while Fassett et.al (1994) presented a similar model with the two secondary compression indices combined into one. Several authors including Wall and Zeiss (1995) and El Fadel and Al-Rashed (1998) tried to curve-fit and create empirical models based, however the fitting was not possible without field measurements and operating values being known in advance.

In more recent years, reseachers began appreciating the contribution of biodegradation with regard to secondary settlement and developed models based on bioreactor landfills. Edgers et.al (2002) developed an empirical settlement model based on 25 considered case studies which accounted for micobiological processes within the landfill, however the method was flawed since the critical time at which the strain rate increase due to biological activity was difficult to determine. Authors such as El Fadel and Al-Rashed (1998) used power creep and one-dimensional consolidation models to analyze data from bioreactor test cells, however Park et.al (2002) indicated power creep model to be a poor predictor of settlement rate.

Following the beginning of considering and separating biodegradation from the inorganic phase of secondary settlement, authors such as Disbrow (1988), Arntz and Raghu (1993) and Gausconi and Raghu (2002), and Lifrieri (2010) contended that this long-term compression is a strain-related phenomenon which is proportional to the rate at which gas is produced, and consequently biodegradable mass is removed from the waste material.

The author believes this is further substantiated as it has been shown that a loss of biodegradable mass occurs as biodegradation progresses, as shown in Figure 2.2. It is therefore hypothesized that the volumetric strain that occurs through decomposition is related to the vertical strain since the thickness of the landfill is substantially smaller than its length and width (plane strain conditions).

While several methods are available for predicting landfill settlement, the majority of these models are outdated and do not accurately account for the time rate of settlement as well as the composition and state of degradation of the waste material. Models based on the chemical process more accurately depict the biodegradation phenomenon.

The author notes that the current models which are frequently used today inaccurately attempt to estimate the settlement by considering a wide set of data which includes a large variations of landfill types, thicknesses, and regional environments which include climate as well as waste composition. Likewise, it is the author's opinion that this empirical method may work for one, discrete model; however, the current authors and methods do not possess a complete understanding of the biodegradation process. The model proposed here overcomes the shortcomings identified above by other currently used models.

CHAPTER 3

A REVIEW OF MSW GAS PRODUCTION

Approximately 250 million tons of MSW were generated in the United States in 2008, with 54 percent of that deposited in landfills. For each one million ton of MSW, roughly 432,000 cubic feet per day of landfill gas is produced over a period of time as long as 20 to 30 years after being landfilled (USEPA 2009). Federal and/or state regulations require most large landfills to collect landfill gas (LFG) and combust it, either by flaring or by using it in an LFG energy system. With a specific heating value of about 500 British thermal units (Btu) per standard cubic foot (EPA 2010, Tchobanoglous 1993), the contribution of landfill gas as a source of energy cannot be overlooked. Aside from the prediction of gas generation for commercial purposes, as indicated in Chapter 2, it is the author's and others opinion that a relationship between the original amount of the waste and the gas and biomass remaining each year can be used to predict the long-term settlement behavior of the landfilled waste.

3.1 Review of Industry Accepted Gas Production Models and Gas Production

The wide range in types of waste, composition, and environments suggest that no basic equation or rate constant has been developed to accurately describe the rate of decomposition and landfill gas generation within a landfill. However, the majority of authors and practitioners use the USEPA LandGEM model which is based on weight (in tons) placed in the landfill, a default standard first-order decay constant, and a default specified theoretical potential of methane potential per ton of waste (USEPA 2005).

The author clarifies that the decay constant suggested by the LandGEM model, termed "k", is obtained from a graph of the rate of gas production with respect to time (dy/dt). In attempts to refine gas production models, several authors (Barlaz et. al 2010, Tolaymat et. al 2010, Durmusoglu et al. 2005, Metha et. al 2002, Pacey et. al 1996, Findikakis 1979) have suggested half-lives of various waste components. The author notes that the waste half-life is obtainable by plotting cumulative gas remaining versus time; therefore, this half-life constant is not directly interchangeable with the decay constant ("k") used by the LandGEM model. To avoid confusion the author has suggested the use of the lambda symbol ("λ"), as suggested by Durmusoglu et al. 2005 and Findikakis 1979 to represent the half-life constant of various wastes. The differentiation is depicted graphically in Figure 3.1. It is commented that the starting point for estimating cumulative gas remaining is based on calculated theoretical maximum gas potential from several methods, which include cumulative gas production versus time, and are detailed elaborately in Chapter 3 and 5.

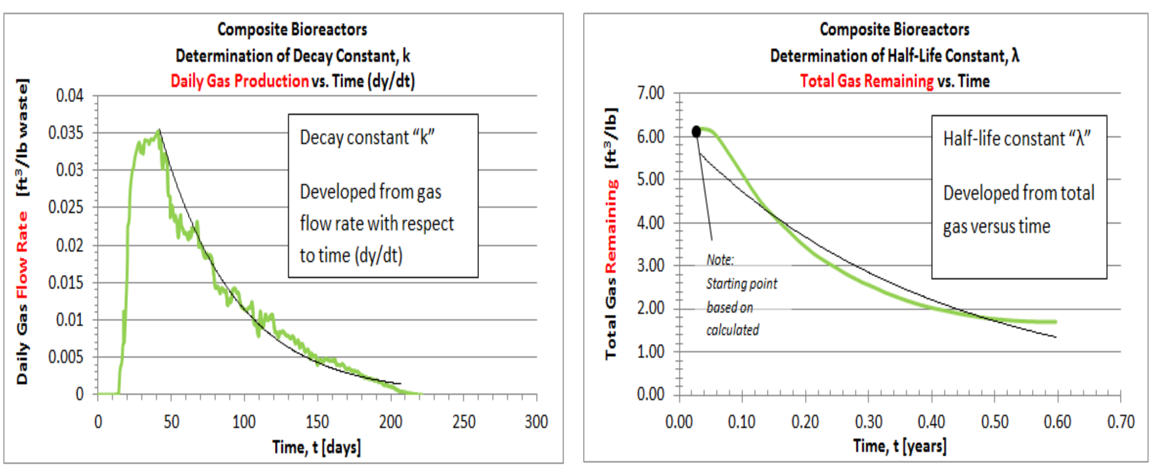

Figure 3.1 Comparison of Decay Constant, "k", and Half-life Constant, "λ"

While the LandGEM model was originally developed for traditional landfills, recent updates to the model allow it to be used for "wet" (bioreactor) landfills which consider leachate recirculation. The first-order decomposition rate equation used by the model is:

$$Q_{CH4} = \sum_{i=1}^{n}\sum_{j=0.1}^{1} kL_0\left(\frac{M_i}{10}\right)e^{-kt_{ij}} \qquad (3.1)$$

Where Q_{CH4} represents actual calculated annual methane generation in the year of calculation (m^3/year), "i" is the time increment, n is the year of calculation, and "j" is the integration time increment (generally a time step of 0.1 years is evaluated). The equation uses "k" to represent the methane generation rate, which is not synonymous with half-life decay constant used by others (Durmusoglu et al. 2005, Findikakis 1979). Suggested methane generation rates vary between 0.02 $year^{-1}$ for arid areas to 0.7 $year^{-1}$ for wet (bioreactor) landfills. A default theoretical generation rate of 0.05 $year^{-1}$ is used by most end-users of the model as recommended by guidance to conform to Clean Air Act emission planning requirements. The variable M_i represents mass of solid waste disposed in the i^{th} year (in ton or megagram), while L_o is the estimated theoretical potential methane generation capacity of the waste in cubic feet per ton or cubic meter per megagram.

The estimated theoretical potential methane generation capacity is generally taken as 170 cubic meter per megagram, or 2.72 cubic feet per pound waste. It should be noted that the model determines total landfill gas generation assuming a distribution of 50 percent methane and 50 percent carbon dioxide, an industry standard distribution. Therefore, the potential total gas generation capacity at this distribution is 5.45 cubic feet per pound waste. A comparison of estimated theoretical total gas generation based on various methods is provided in Table 6.3 in Chapter 6.

Should a different composition of gas be required, the amount of methane and carbon dioxide may be evaluated using Equation 3.2. The total gas may then be determined using Equation 3.3. The percentage of the methane in the gas, P_{CH4}, is evaluated as a fraction in both equations. Derivations are provided in Appendix F.

$$Q_{CO2} = Q_{CH4} \times \{[1/(P_{CH4}/100)] - 1\} \qquad (3.2)$$

$$Q_{total} = (Q_{CH4} + Q_{CO2}) = \frac{Q_{CH4}}{P_{CH4}} \qquad (3.3)$$

Graphically, the gas production curves of this model for both the traditional and bioreactor landfill cases are shown as Figure 3.2. It should be noted that there is a distinctively higher peak and shorter decay time for the bioreactor landfill as a result of the increased decay rate constant, however the total volume of methane produced remains constant.

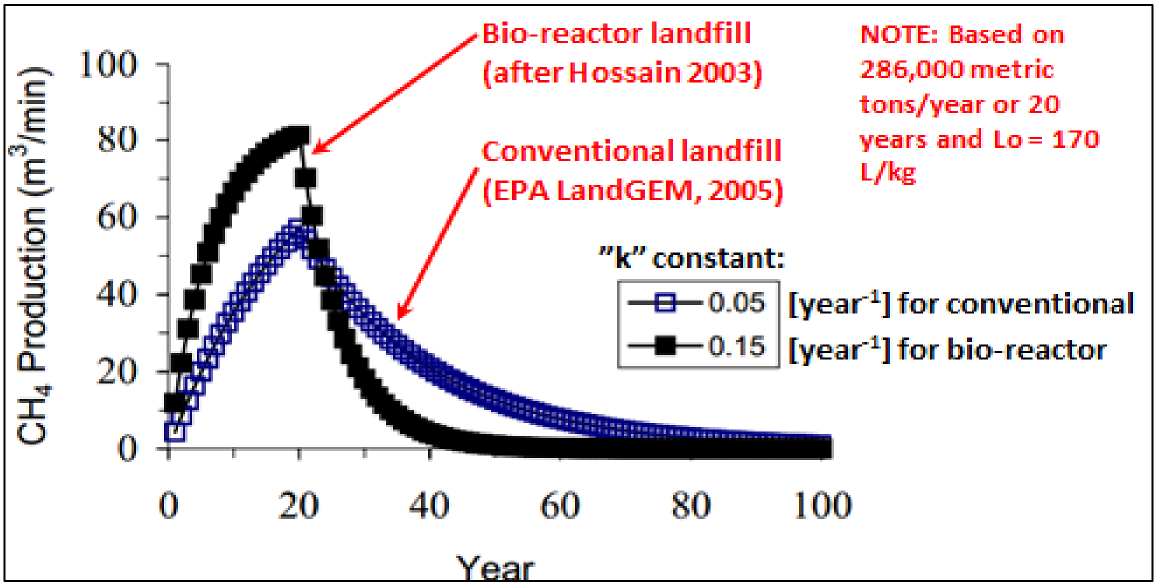

Figure 3.2 USEPA LandGEM gas production model for conventional and enhanced decomposition (bioreactor) landfills
Source: Hossain (2003)

Prior to the EPA LandGEM model, gas production distribution was characterized using the SIMCON model proposed by C.S. Hollings and originally for simulation of population decay. The SIMCON model proposed the rate of gas production occurs at an inverse proportion with exponential of time. The model was modified by Disbrow (1988), and later used by Arntz and Raghu (1993) and Raghu and Gausconi (2002). The model defined the onset of gas generation occurring at a constant rate until it reaches a maximum daily production of gas (identified as t_1 and taken as 10 years in non-bioreactor landfills) then eventually a decreasing rate of daily gas production. The model assumed approximately 90 percent of gas production would occur within the first 40 years of landfilling. This characteristic shape of this model (depicted as Figure 3.3) is nearly identical to the LandGEM model as it exhibits a more pronounced and early-occurring peak due to the introduction of leachate as well as conditions to promote the landfill as a bioreactor instead of the typical dry entombment.

The total theoretical gas production for each phase can be determined by Equations 3.4 and 3.5. Derivations for equations have been presented in Appendix F.

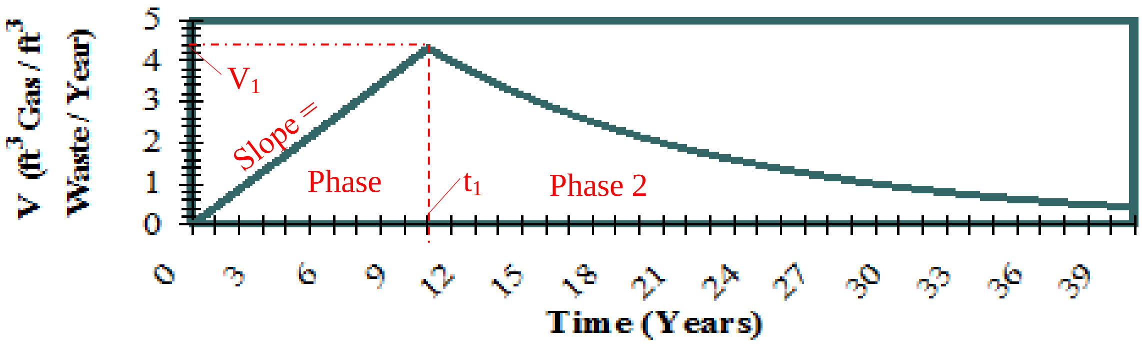

Figure 3.3 Gas Production Curve for the Raghu and Gausconi Model (2002)

This linear onset of gas production is during the occurrence of inorganic secondary compression as anaerobic decomposition begins to start and eventually transitions into biodegradation settlement as daily gas production reaches a peak and begins to decrease.

For Phase 1 ($t_n \leq 10$ years):

$$V_{phase\ 1} = \frac{V_o' t_n^2}{2} \tag{3.4}$$

For Phase 2 ($t_n > 10$ years):

$$V_{phase2} = \frac{-V_1}{k} e^{-k(t-10)} + C \tag{3.5}$$

Therefore, total volume may be expressed as:

$$V_{total} = V_{phase\ 1} + V_{phase\ 2} = V_o^{'}(\frac{t_1^2}{2} - \frac{10}{k}e^{-k(t-10)}) + C \qquad (3.5)$$

Values for each parameter, 0.076753, 1.335, and 13.35 for k, V_o, and V_1 were obtained by the Raghu and Gausconi based on data from a landfill constructed in 1985 which had undergone 15 years of degradation. Based on these values, the authors predicted a total gas production of 223.2 cubic feet of gas per cubic feet waste. Using a waste density of 40 pounds per cubic foot representative of moderate to good waste compaction (Tchobanglous 1993, Oweis and Khera 1998), the model predicts a total gas potential of 5.58 cubic feet per pound waste. This is within 3 percent of the EPA LandGEM model.

In both models, the decrease in gas production after peak occurs similar to a first-order decay reaction with decay constant “k”. It is the author’s hypothesis that this decay constant is a representation of the decay constants of the individual proportions of waste types (readily, moderately, and slowly degradable) and that a decay constant for any composite waste type can be predicted by proportioning individual decay constants formulated by this work to match the waste composition.

This author notes an important clarification that theoretical gas production is based on total wet weight of the waste material as placed which follows industry standard, and not normalized per pound of dry waste (Manley 1993).

In select models, such as stoichiometric or chemistry-based models, the dry weight of the waste must be used to avoid the contribution of hydrogen and oxygen and additional molecular mass by water; however, the resultant gas production should be normalized per pound of waste reported wet. Landfill operators have adopted this industry standard for its ease to provide a directly measurable correlation of as-tipped weight to gas production without the additional step of drying waste samples.

3.2 Prediction of Gas Production by Stoichiometry, Mass Balance, and Chemical Relationships

Several authors have attempted to predict landfill gas generation by evaluating the individual waste components at an elemental level (Ham et al. 1979, Tchobanoglous 1993, Barlaz 1990). Generally, the accepted reaction mechanism is a first-order reaction with inputs of organic waste and water, and outputs of biodegraded organic matter, methane, carbon dioxide, and other trace gases. Ham et al. (1979) proposed a generalized equation describing this process, which is provided as Equation 3.6.

$$C_aH_bO_cN_dS_e + \left(\frac{4a-b-2c+3d+e}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d-e}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d+2e}{8}\right)CO_2 + dNH_3 + eH_2S \tag{3.6}$$

Recognizing the de minimis quantity of sulfur in most waste components and consequently negligible quantities of hydrogen sulfide gas in comparison to others, Tchobanoglous (1993) suggested a modified equation. This equation is presented as Equation 3.7 and is the generally accepted form of the model used in industry.

$$C_aH_bO_cN_d + (\frac{4a-b-2c+3d}{4})H_2O \rightarrow$$
$$(\frac{4a+b-2c-3d}{8})CH_4 + (\frac{4a-b+2c+3d}{8})CO_2 + dNH_3 \qquad (3.7)$$

In the given models, parameters *a*, *b*, *c*, *d*, and *e* represent the molar quantity of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) and are calculated based on the composition of the waste. The percent by weight (dry basis) for each waste constituent and an example calculation to determine parameters is presented in Table 3.1.

The waste composition evaluated for this research has been used to provide example calculations. Calculations are based on a dry sample weight of 100 pounds. Additional background on waste composition is provided in Chapter 4.

It is suggested by Tchobanoglous (1993) to split the waste into two classifications, readily and slowly degradable, and evaluate the contribution of each to determine the total theoretical gas composition of the waste. Example calculations shown herewith show the gas production without separation of the fractions; however, calculations provided in Appendix G include analyses for the waste separated into readily and moderately degradable fractions.

It has been determined by the author and others (Shah et. al 2007, Ishigaki et al. 2003, Tchobanoglous 1993, Albertson et. al, 1987) that the use of this model to predict the gas production for plastics (which comprise the "slowly" composition waste used during this research) is inappropriate as the model greatly overestimates the theoretical gas production. As the nitrogen content of plastics is diminutive in comparison to other elements, normalization with respect to nitrogen will produce an elemental expression of the waste with exaggerated proportions of carbon, hydrogen, and oxygen, and thusly an overestimated theoretical gas production.

Once the parameters *a*, *b*, *c*, *d*, and *e* and the elemental expression of the waste are determined, the constants for each product, H_2O, CH_4, CO_2, and NH_3, can be determined. The specific mass of each component may be tabulated to determine the volume of gases produced. This process is presented as Table 3.2.

Table 3.1 Typical Data for Select Waste Components in Residential MSW and Determination of Molecular Mass for Components
Source: Tchobanoglous (1993), p. 81

<table>
<tr><th rowspan="2"></th><th rowspan="2">Component</th><th rowspan="2">Type</th><th rowspan="2">Dry Weight [lb]</th><th colspan="6">Percent by Weight (dry basis)</th></tr>
<tr><th>C</th><th>H</th><th>O</th><th>N</th><th>S</th><th>Ash</th></tr>
<tr><td rowspan="10">STEP 1</td><td>Food</td><td>R</td><td>19.05</td><td>48</td><td>6.4</td><td>37.6</td><td>2.6</td><td>0.4</td><td>5</td></tr>
<tr><td>Yard Waste</td><td>R</td><td>6.19</td><td>47.8</td><td>6</td><td>38</td><td>3.4</td><td>0.3</td><td>4.5</td></tr>
<tr><td>Wood</td><td>M</td><td>1.90</td><td>49.5</td><td>6</td><td>42.7</td><td>0.2</td><td>0.1</td><td>1.5</td></tr>
<tr><td>Paper</td><td>M</td><td>38.10</td><td>43.5</td><td>6</td><td>44</td><td>0.3</td><td>0.2</td><td>6</td></tr>
<tr><td>Textiles</td><td>M</td><td>2.86</td><td>55</td><td>6.6</td><td>31.2</td><td>4.6</td><td>0.15</td><td>2.5</td></tr>
<tr><td>Plastic</td><td>S</td><td>12.38</td><td>60</td><td>7.2</td><td>22.8</td><td>0</td><td>0</td><td>10</td></tr>
<tr><td>Soil</td><td>I</td><td>8.10</td><td>26.3</td><td>3</td><td>2</td><td>0.5</td><td>0.2</td><td>68</td></tr>
<tr><td>Glass</td><td>I</td><td>10.95</td><td>0.5</td><td>0.1</td><td>0.4</td><td>0.1</td><td>0</td><td>98.9</td></tr>
<tr><td>Metal</td><td>I</td><td>0.48</td><td>4.5</td><td>0.6</td><td>4.3</td><td>0.1</td><td>0</td><td>90.5</td></tr>
<tr><td colspan="2">Total Weight:</td><td>100.00</td><td colspan="6">R= Readily, M = Moderate, S= Slow, I = Inert</td></tr>
<tr><td rowspan="12">STEP 2</td><td colspan="3" rowspan="2">Example calculations and notes:</td><td colspan="6">Composition [lb]
(listed in same order of components as Step 1)</td></tr>
<tr><td>C</td><td>H</td><td>O</td><td>N</td><td>S</td><td>Ash</td></tr>
<tr><td colspan="3">C in food = 19.05 lb x 48% = 9.14 lb</td><td>9.14</td><td>1.22</td><td>7.16</td><td>0.50</td><td>0.08</td><td>0.95</td></tr>
<tr><td colspan="3">H in food = 19.05 lb x 6.4% = 1.22 lb</td><td>2.96</td><td>0.37</td><td>2.35</td><td>0.21</td><td>0.02</td><td>0.28</td></tr>
<tr><td colspan="3">O in food = 19.05 lb x 37.6%= 7.16 lb</td><td>0.94</td><td>0.11</td><td>0.81</td><td>0.00</td><td>0.00</td><td>0.03</td></tr>
<tr><td colspan="3">N in food = 19.05 lb x 2.6% = 0.50 lb</td><td>16.57</td><td>2.29</td><td>16.76</td><td>0.11</td><td>0.08</td><td>2.29</td></tr>
<tr><td colspan="3">S in food = 19.05 lb x 0.4% = 0.08 lb</td><td>1.57</td><td>0.19</td><td>0.89</td><td>0.13</td><td>0.00</td><td>0.07</td></tr>
<tr><td colspan="3">Ash in food = 19.05 lb x 5% = 0.95 lb</td><td>7.43</td><td>0.89</td><td>2.82</td><td>0.00</td><td>0.00</td><td>1.24</td></tr>
<tr><td colspan="3" rowspan="3">Total carbon in sample =
∑ carbon (food + … + textiles)</td><td>2.13</td><td>0.24</td><td>0.16</td><td>0.04</td><td>0.02</td><td>5.50</td></tr>
<tr><td>0.05</td><td>0.01</td><td>0.04</td><td>0.01</td><td>0.00</td><td>10.8</td></tr>
<tr><td>0.02</td><td>0.00</td><td>0.02</td><td>0.00</td><td>0.00</td><td>0.43</td></tr>
<tr><td colspan="3">Total, decomposable (R,M,S) portion:</td><td>38.62</td><td>5.07</td><td>30.80</td><td>0.96</td><td>0.18</td><td>4.85</td></tr>
<tr><td rowspan="3">STEP 3</td><td colspan="3">Specific weight = molecular mass</td><td colspan="6">Specific Weight [lb/mole]</td></tr>
<tr><td colspan="3" rowspan="2">Molar composition of C =
38.62 lb/12.01 lb/mol = 3.21 mol</td><td>12.01</td><td>1.01</td><td>16.00</td><td>14.01</td><td>32.06</td><td></td></tr>
<tr><td colspan="6">Molar Composition [mole]</td></tr>
<tr><td rowspan="2">STEP 4</td><td colspan="3" rowspan="2">Sulfur neglected; Composition normalized with respect to N</td><td>3.215</td><td>5.020</td><td>1.925</td><td>0.068</td><td>0.006</td><td></td></tr>
<tr><td colspan="6">Normalized Molar Composition [mole]</td></tr>
<tr><td rowspan="2">STEP 5</td><td colspan="3">Parameter a, (Normalized Carbon) =
(3.215/.006) = 47.16</td><td>C, a
47.16</td><td>H, b
73.63</td><td>O, c
28.24</td><td>N, d
1.00</td><td>S, e
0.00</td><td></td></tr>
<tr><td colspan="3">Chemical expression of waste:</td><td colspan="6">$C_{47.2}H_{76.6}O_{28.2}N$</td></tr>
</table>

Table 3.2 Calculation of Theoretical Gas Production by Stoichiometry

Example calculations to determine gas production:

STEP 6

Equation Components

H_2O	CH_4	CO_2	NH_3
15.4	25.3	21.8	1.0

Component of H_2O= (4a - b - 2c + 3d)/4= (4*47.16 - 73.63 - 2*28.24 + 3)/4 = **15.4**

STEP 7

Specific (Molecular) Weight [lb/mole]

C	H	O	N
12.01	1.01	16.00	14.01

Elemental Specific Weight [lb/mole]

H_2O	CH_4	CO_2	NH_3
18.02	16.05	44.01	17.04

Ex.: Elemental weight of H_2O = 1.01 lb/mol (2) + 16 lb/mol (1) = 18.02 lb/mol
Elemental weight of $C_aH_bO_cN_d$ = 12.01(47.16) + 1.01 (73.63) + 16 (28.24) + 14.01

Reaction Masses

$C_aH_bO_cN_d$ +	H_2O --->	CH_4 +	CO_2 +	NH_3
1106.5	277.2	406.8	959.8	17.0

Example: reaction mass of H_2O = (15.4 mol)(18.02 lb/mol) = 277.2 lb
∑ Right Side = 406.8 + 959.8 + 17 = 1383 ∑ Left Side= 1106.2 + 277.2 =1383

Volume methane produced, $V_{CH4} = (M_{CH4})(W_{degradable}) / [(M_{CaHbOcNd})(W_{CH4})$
Volume methane produced, $V_{CO2} = (M_{CO2})(W_{degradable}) / [(M_{CaHbOcNd})(W_{CO2})$

CH_4 Gas Specific Weight, W_{CH4} [lb/ft³] = 0.0448
CO_2 Gas Specific Weight, W_{CO2} [lb/ft³] = 0.1235

V_{CH4} = [(406.8)(80 lb degradable waste)]/[(1106.5)(0.0448 lb/ft3)] = 656.8 ft^3
V_{CO2} = [(959.8)(80 lb degradable waste)]/[(1106.5)(0.1235 lb/ft3)] = 561.6 ft^3
Total volume of gas = $V_{CH4} + V_{CO2}$ = 1218.4 ft^3
Proportion of CH_4 of gas = 656.8/1218.4 = 54%
Proportion of CO_2 of gas = 561.6/1218.4 = 46%

STEP 8

Average moisture content of MSW waste as tipped = 25% (Tchobanoglous 1993)
Wet weight of waste = dry weight x (1 + m.c.) = 100 lb x (1 + 0.25) = 125 lb
Theoretical gas production by stoichiometry:
= 1218.4 ft^3/125.0 lb = **9.75 ft^3/lb (wet)**

From the calculations, it is possible to determine the minimum moisture content required to support the reaction. The required moisture content can be calculated by dividing the reaction mass of water by the reaction mass of the elemental waste expression. The required moisture content for the example presented is 25 percent, which falls between the required range of 15 to 40 percent observed by others (Pohland 1994, USEPA 2005, Oweis 1990, Tchobanoglous 1993, Barlaz 1990).

The author comments that the value of theoretical gas produced represents an upper boundary of the maximum amount of gas which could be produced under optimum conditions and of complete biodegradation of all organic fractions of the MSW. The model also assumes a complete conversion of the organics to solely methane, carbon dioxide, and minimal ammonia. Actual quantities of gas produced will be much lower as not all organic material may be bio-accessible, for instance paper contained tightly within closed plastic bags or material shadowed from receiving leachate. Organic wastes which are also not exposed to sufficient moisture to sustain biologic activity have a decreasing tendency to be converted. It has been shown that landfills lacking sufficient moisture for biodegradation will leave contents in a “mummified” condition (Tchobanoglous 1993). Other trace gases and vapors, including carbon monoxide, volatiles may also be created.

Several authors have noted that published data on waste composition was used to determine theoretical gas production and, when compared to actual full-scale landfill gas collection records, actual yields were between 1 and 50 percent of the calculated theoretical from stoichiometry (Barlaz et al. 1990, Barlaz et al. 1989). Similarly, under it has been estimated that 30 to 50 percent of the theoretical gas generated could be achieved within two years, and up to 70 percent within 5 years (Tchobanoglous 1993).

3.3 Prediction of Gas Production by Lambda Method and Half-Life Decay Factors

Aside from the first-order decomposition and stoichiometric models for gas production, others have attempted to estimate gas production empirically through regression analyses and modifications to the concept of half-life decay. Findikakis and Leckie (1979) developed the first model to relate the half-life decay concept to landfill gas production. The approach required a waste characterization, physical description of the waste constituents, and their individual decomposition rates.

The work by the authors suggested that the organic portion of the waste could be characterized by one of three measures of biodegradability of the waste: readily, moderately, or slowly biodegradable. Readily biodegradable wastes consisted of food and vegetative constituents, while moderately wastes consisted of leather, paper products and newsprint, textiles, and wood. Slowly biodegradable components consisted of plastic, rubber, and organic soil. Half-lives (t_{50}) of 5, 30, and 40 years for the readily, moderately, and slowly biodegradable waste categories, respectively, were recommended by the authors. The gas production rate constant, λ_i , could then be determined by first-order kinetics using Equation 3.8. Values for gas production constants for readily, moderately, and slowly degradable wastes are subsequently calculated to be 0.1386 year^{-1}, 0.0231 year^{-1}, and 0.0173 year^{-1}, respectively.

$$\lambda_i = \frac{-\ln(1/2)}{t_{i_{50}}} = \frac{0.693}{t_{i_{50}}} \tag{3.8}$$

Durmusoglu et al. (2005) theorized a similar variation of the original model, and introduced the concept of the total gas production rate to develop both the gas remaining and cumulative gas production relationship, which follows exactly the opposite pattern of cumulative gas production. To determine gas generation rate, α_i , and total gas production potential, G_T^i, at any time following placement of waste, Durmusoglu et al. developed Equations 3.9 and 3.10. The equations would be applied to each waste of the three waste types and summed to determine the overall rate and potential at any given time for the composite waste mass.

$$\alpha_i = \lambda G_i e^{-\lambda t} \tag{3.9}$$

$$G_p^i = G_T^i A_i e^{-\lambda_i t} \tag{3.10}$$

In the model G_T^i represented total theoretical gas production potential for each waste type, which was suggested by Durmusoglu et. al (2005) as 9.40 lbs/ft^3, 14.1 lbs/ft^3, and 7.83 lbs/ft^3 for the readily, moderately, and slowly biodegradable categories. The variable A_i corresponded to the fraction of MSW represented by each category. To determine the gas production rate for a composite waste sample at any time, t, the author hypothesizes that the individual gas production rates could be summed. It is partially the aim of this work to validate this assumption. This author has expressed this hypothesis as Equation 3.11.

$$\alpha_C = G_T^r A_r \lambda_r e^{-\lambda_r t} + G_T^m A_m \lambda_m e^{-\lambda_m t} + G_T^s A_s \lambda_s e^{-\lambda_s t} \quad (3.11)$$

Lifrieri (2010) refined the use of the Lambda method model developed by Durmusoglu et al. by completing iterative analyses to determine the approximate end of biodegradation and theoretical total gas production by integration over this time span. Lifrieri suggested identifying the time at which 97 percent of the organic portion has been degraded, which represents the practical limit of degradation where additional gas production becomes insignificant. By calculating the total volume of gas production at the practical end of degradation one can normalize the gas produced per pound of waste.

An example calculation to determine the gas production at any time of interest for a composite waste sample consisting of readily, moderately, slowly, and non-degradable constituents is provided as Table 3.3. The determination of the maximum theoretical gas production of the waste types comprising this composition is shown in Table 3.4. The examples are based on a composition of waste as used for this experiment, consisting of 25 percent readily biodegradable waste (food and garden waste), 43 percent moderately biodegradable waste (paper, wood chippings, and textiles), 13 percent slowly degradable waste (plastic), and 19 percent non-biodegradable waste (glass, soil/ashes, metals). Additional details regarding the basis for the composition selected are provided in Chapter 4. The author believes the model provides better correlations to actual degradation of waste mass as measured at the conclusion of this work compared to other models.

Table 3.3 Example Calculation of Gas Production by Lambda Method

STEP 1

Step 1: Break out composition into % descriptive modifiers

Inputted				Calculated				
Waste	Type	% MSW	Wet Wt [lb]	V_i	% of Type	Dry weight	W_i [lb]	Total Wt [lb]
Food Yard Waste	R R	19% 6%	19 6	V_r =	25%	9.62 3.04	W_r =	12.65
Wood Paper Textiles	M M M	2% 38% 3%	2 38 3	V_m =	43%	1.01 19.23 1.52	W_m =	21.77
Plastic	S	13%	13	V_s =	13%	6.58	W_s =	6.58
Soil Glass	ND ND	8% 11%	8 11	V_n =	19%		W_n =	0.00
Decomposable Moist Wt=			81 lb	V_t =	100%	41.00	Dry Wt	

V_i = Volume of Type of Waste W_i = Weight of Type of Waste (based on 100 lb sample)

Average moisture content of waste, m.c. = 40%

NOTE: moisture content defined as W_{water}/W_{tot}, unlike geotech definition of W_w/W_{dry}

For 100lb wet sample, weight of water = W_{tot} x m.c. = 0.4 * 100lb = 40 lb

Wt of decomposable fraction - all water contained in waste= 81 - 40 lb = 41 lb

STEP 2

Step 2: Determine Lambda (Half-Life) Factors

Characteristic equation: $V_{ti} = V_i\, e^{-(\lambda it)}$

λ_r = 0.1386

λ_m = 0.0231

λ_s = 0.0173

STEP 3

Step 3: Select year of interest to determine modifier, V_i

For this example, use 30 year

Readily: $V_r@30yrs = (25)\, e^{-[(0.1386)(30)]}$ = 0.00391

Moderately: $V_m@30yrs = (43)\, e^{-[(0.0231)(30)]}$ = 0.21503

Slowly: $V_s@30yrs = (13)\, e^{-[(0.0173)(30)]}$ = 0.07736

STEP 4

Step 4: Determine % decomposed

% decomposed = $(V_i - V_{it})/V_i$

Readily: $\%D_r$ = (0.25-0.00391)/0.25 x 100% = 98%

Moderately: $\%D_m$ = (0.43-0.215)/0.26 x 100% = 50%

Slowly: $\%D_s$ = (0.13-0.0774)/0.27 x 100% = 40%

STEP 5

Step 5: Determine (dry) weight of decomposed organics

Weight of decomposed organics = % decomposed x dry weight fraction

Readily: 98% x (12.65 lb) = 12.46 lb

Moderately: 50% x (21.77 lb) = 10.88 lb

Slowly: 40% x (6.58 lb) = 2.66 lb

Total decomposed weight, $W_{degraded}$ = 26.00 lb

Table 3.4 Example Calculation of Gas Production by Lambda Method (continued)

STEP 6	**Step 6: Determine gas produced using stoichiometric reaction masses** Reaction Masses from stoichiometry (Calculated in Table 3.1) $C_aH_bO_cN_d$ = 1106.5 CH_4 = 406.8 NH_3 = 17 H_2O = 277.2 CO_2 = 959.8
STEP 7	**Step 7: Determine volume of gas produced up to time, *t*** (30 years for example) Volume methane produced, $V_{CH4} = (M_{CH4})(W_{degraded}) / [(M_{CaHbOcNd})(W_{CH4})$ V_{CH4} = [(406.8)(26.00)] / [(1106.5)(0.0448)] = 213.38 ft^3 V_{CO2} = [(959.8)(26.00)] / [(1106.5)(0.1234)] = 182.78 ft^3 Total gas, $V_{total} = V_{CH4} + V_{CO2}$ = 396.16 ft^3 % CH4 = 54% %CO_2 = 46% Theoretical gas produced per lb waste up to 30 years= V_{total}/sample weight Gas production at time t (30 years) = 626.12 ft^3/100lb = 3.96 ft^3/lb

Table 3.5 Calculation of Maximum Theoretical Gas Production by Lambda Method

To find max theoretical gas production, solve characteristic equation for when V_{ts}= 95% (volume of slowly decomposable material reaches 95% degradation solving, t = 173 yr		
Step 3: Select year of interest to determine modifier, V_i (t=173 years)		
Readily:	V_r@173yrs = (25) $e^{-[(0.1386)(173)]}$ =	9.65E-12
Moderately:	V_m@173yrs = (43) $e^{-[(0.0231)(173)]}$ =	7.90E-03
Slowly:	V_s@173yrs = (13) $e^{-[(0.0173)(173)]}$ =	6.52E-03
Step 4: Determine % decomposed		
Readily:	(0.25-(9.56E-12))/0.25 x 100% =	100%
Moderately:	(0.43-(7.90E-03))/0.43 x 100% =	99%
Slowly:	(0.13-(6.52E-03))/0.13 x 100% =	95%
Step 5: Weight of decomposed weight = % decomposed x dry weight fraction		
Readily:	100% x (12.65 lb)	12.65 lb
Moderately:	99% x (21.77 lb)	21.77 lb
Slowly:	95% x (6.58 lb)	6.46 lb
	Total decomposed weight=	40.88 lb
Step 6: Determine gas produced using stoichiometric reaction masses (use as above)		
Step 7: Determine volume of gas produced up to time, *t* (t =173 years)		
	V_{CH4} = [(406.8)(40.88)] / [(1106.5)(0.0448)] =	335.47 ft^3
	V_{CO2} = [(959.8)(40.88)] / [(1106.5)(0.1234)] =	287.35 ft^3
	Total gas, $V_{total} = V_{CH4} + V_{CO2}$ =	622.82
	% CH_4 = 54%	%CO_2 = 46%
At end of practical biodegradation, theoretical total gas produced = 622.82 ft^3		
Gas production at practical end of degradation (t=137 yr)= 622.82 ft^3/100lb = **6.23 ft^3/lb**		

3.4 Discussion on Limitations of Existing Models for Estimating Gas Production

The wide variation of wastes, and even fractions within waste such as food types, types of paper, and presence of white good and outliers, inherently suggest that no simple equation of rate constant will capture the magnitude and time rate of decomposition of landfill gas generation from a landfill. Several authors have indicated that there is insufficient field data available from MSW landfills which allow for verification of kinetic and rate-order models to describe the time dependency of gas production (Manley 1992, Barlaz et al. 1990, 1989, Schumacher 1983). The author suggests that these observations by others and this work indicate that stoichiometry alone is not suitable to predict landfill gas production.

Further, it can be observed that almost all gas production models evaluate the production of solely both methane and carbon dioxide as general end-products of the decomposition process. However, numerous studies have shown typical landfill gas composition to consist of between 45 to 60 percent methane, 40 to 50 percent carbon dioxide, 2 to 5 percent nitrogen, and up to 1 percent ammonia (USEPA 2005, 2010; Tchobanoglous 1993; Barlaz et. al 1990, 1989, Farquahar 1973, Palmisano 1996). The use of these models to predict the volume of these gases for landfills that have methane content outside the range of 40 to 60 percent is not recommended as assumptions for the first-order decomposition rate equation may not be valid outside of this range (USEPA 2005).

The use of these existing gas production models to calculate the quantity of other landfill gases is also impractical or generally discouraged. While the productions of both gases are several orders of magnitude greater than other landfill gases, the simple assumption consequently assumes a complete conversion of all solid matter to gas. The author notes that this is an incorrect assumption as components such as lignin, other non-bioaccessible matter, and inert material will stay within the landfill and will not be converted to methane or carbon dioxide. Additionally, the assumption does not consider that any matter leaving the landfill, in gas form or dissolved and carried and flushed out of the system by leachate, would contain any organic material. The author believes this to be a fatal flaw of most models, and a reason why over predictions are generally observed by each model. However, methane and carbon dioxide are the primary constituents measured by owner and operators, with methane generation being the focus of this work.

In addition to variation of waste, there is general oversimplification of models as they do not account for the influences of significant variables such as moisture content, degree of compaction, particle size, temperature, nutrient availability, and other driving conditions for gas production. For example, the effect of particle size and impact on decomposition has been studied by several investigators, and has been determined to be inconclusive (Barlaz et al 1990, Pohland 1986), with an inclination toward smaller particle size. Although it would appear that shredded refuse with particle size less than 3 inches would permit greater contact between microorganisms, substrates and nutrients, and moisture, the smaller size may promote an increase in hydrolysis which may lead to a build-up of acidic end products and a lower pH, thus resulting in lower gas production potential (Barlaz et al. 1990, Ham 1982, Buivid et al. 1981, DeWalle et al. 1978).

In many closed landfills the available moisture is insufficient to allow for the complete conversion of the biodegradable fraction of waste. Tchobanglous (1993) and Chian and DeWalle (1979) recommend an optimum moisture content for landfills on the order of 43 to 60 percent as, in many landfills, the moisture that is present is not uniformly distributed and a higher moisture content may support the zones of lower moisture. A minimum of 15 to 25 percent moisture content is required based on the governing chemistry and stoichiometry for the degradation reaction as shown above, with most sources observing moisture contents between 15 to 40 percent are optimal for decomposition (Pohland 1994, USEPA 2005, Oweis 1990, Tchobanoglous 1993, Barlaz 1990). It has been shown that landfills lacking sufficient moisture for biodegradation will leave contents in a “mummified” condition (Tchobanoglous 1993).

In addition, Manley (1992) indicates there is the likelihood that the composition of the gas produced and measured at the landfill will not be as calculated because of the much higher solubility of carbon dioxide in water than methane. It is indicated that this consideration alone suggests that the greater the moisture content of the refuse, the higher the methane concentration will be in the gas although the amount of gas generated per volume of refuse will remain unchanged. The author comments that the work conducted herein maintained moisture content within a range of 40 to 45 percent to promote biodegradation.

The availability of nutrients is critical in the decomposition process as carbon, hydrogen, nitrogen, and phosphorus must be present in sufficient quantities to drive forward reaction chemistries supporting degradation. One author (Ham 1979) indicates that general assumptions are made that all refuse components, such as carbohydrates, proteins, starches, from the readily, moderately, and slowly degradable waste types are available to organisms simultaneously so that a balance of substrates and nutrients are ever present. However, this is not the case as different components, such as readily degradable wastes, will allow conversion earlier than other types depending on the cellulose, hemicellulose, lignins and other natural fibers comprising the waste material. The models assume that all organics will be decomposed; however, lignin is not degradable to any practical extent under anaerobic conditions (Manley 1993, Barlaz 1990, Pohland 1998, Ham 1979) and would elevate theoretical gas production capacity.

Temperature and pH effects similarly influence gas production, with pH having been found to be a reliable indicator of methane generation rates in MSW (Manley 1992). Several authors suggest that the optimum pH range for methogenic bacteria exists near neutral pH, between 6.4 and 7.4 (Barlaz 1990, Pohland 1986, Schumacher 1983). Schumacher (1983) cites that, during methane generation, the average pH of a landfill does not drop below 6.2, which Tchobanoglous (1993) corroborates and attributes to the conversion of acids and hydrogen gas by acid formers to methane and carbon dioxide. Farquhar and Rovers (1973) suggest that deviations from this range of pH may result in reduced gas production.

Manley (1992) cites that temperature effects on methane production are generally classified as thermophilic (greater than 104 °F), mesophilic (between 68 to 104 °F), or psychrophilic (less than 68 °F). Generally, it has been observed that increased gas production occurs up to an optimal temperature of approximately 110 to 120 °F, and drastically decreases below 100 °F or above 140 °F. Farquhar and Rovers (1973) emphasize the sensitivity of methane production, and indicate that changes in temperature as small as 2 °F may disturb methane production. In this work, the temperature of the water bath was maintained at 110 °F.

Finally, this author proposes that the chemical expression model, which is frequently used in industry to provide a basis for evaluating theoretical gas production, may be non-linear. Under the circumstance of a non-linear reaction, competing reactions are taking place and incomplete byproducts including carbon monoxide and other trace gases may be produced. Similarly, the primary gases may be removed from the system, an example being carbon dioxide which is readily soluble in water and reacting with water to form carbonic acid and detracting from carbon dioxide gas collected.

The author additionally notes that the chemical expression also does not take into the time-rate of gas production, as the calculation is based on a “snapshot” in time when the waste is first fresh. As the gas is produced, the chemical expression of the waste degrades, and the molecules of the waste volatize as carbon, hydrogen, oxygen, and nitrogen are consumed through the reaction process. The author attempted to perform stoichiometric calculations in this manner, assuming the chemical components of the waste degraded with a half-life function similar to that of the waste. The author took time steps at evenly-spaced incremental periods to determine gas production. The resulting evaluation determined a theoretical gas production of 7.52 cubic feet per pound of waste, in comparison to the single-step expression. Therefore it is suggested that the lambda method, as modified by Lifrieri (2010), is a better predictor to established total theoretical gas production.

This author summarizes the work of multiple sources which indicate that, on a wet-weight basis, the theoretical gas production per pound of waste ranges between 3.0 to 8.0 cubic feet per pound of waste, as received. A comparison of models with respect to measured gas production from this work has been provided in Chapter 6.

CHAPTER 4

ASSEMBLY OF TEST SET UP AND DISCUSSION OF TEST PROCEDURE

4.1 Overview of Test Program

The author developed multiple bioreactors simulating a landfill environment to investigate the gas production and settlement characteristics of a typical MSW landfill. Each bioreactor was constructed in components and filled with a homogenized waste sample representative of the sample set. Four homogenized waste sample sets, composite, readily, moderately, and slowly degradable, were created and tested. Bioreactors were connected to a gas collection system, leachate recirculation tubing, and subjected to leachate over a period of approximately 260 days to simulate a landfill environment. Gas production, settlement, and other physical and engineering parameters were measured as these conditions varied.

4.2 Preparation of Bioreactors and Test Equipment

Bioreactors were constructed from two-gallon polypropylene mason jars modified to fit leachate recirculation and gas collection ports and tubing. The set-up of bioreactors is similar to that proposed and completed by Lifrieri (2010). Thirty-four reactors within 4 bioreactor sets were created in total. An assembled bioreactor is depicted in Figure 4.1. The schematic arrangements depicted in Figure 4.2 and Figure 4.3 generally describe the equipment and data acquisition set up used for this work. Figure 4.4 and Figure 4.5 showcase the test set up as assembled for the experiment.

The following steps were completed to create the bioreactor assembly:

- Drill two, ¾" diameter holes in jar caps to accept Tygon inlet for gas collection and leachate injection ports
- Drill one, ¾" diameter hole at bottom of jar to accept Tygon inlet for leachate drain port
- Seal leachate drain port fitting with marine sealant to create water-tight seal at connections to prevent leakage of leachate
- Attach shut-off valves and gas collection and leachate collection tubing to appropriate fittings
- Fill bottom 1/3 of each reactor jar with clean pea gravel to act as drain layer. Overlay gravel with geotextile filter fabric
- Install moisture content probe (PICO 64 manufactured by IMKO) into one reactor of each sample set to obtain moisture content for leachate recirculation in a non-destructive manner. Details are provided in Appendix B.5 – Moisture Content Meter Records.
- Prepare representative waste constituents

Figure 4.1 Assembled Bioreactor

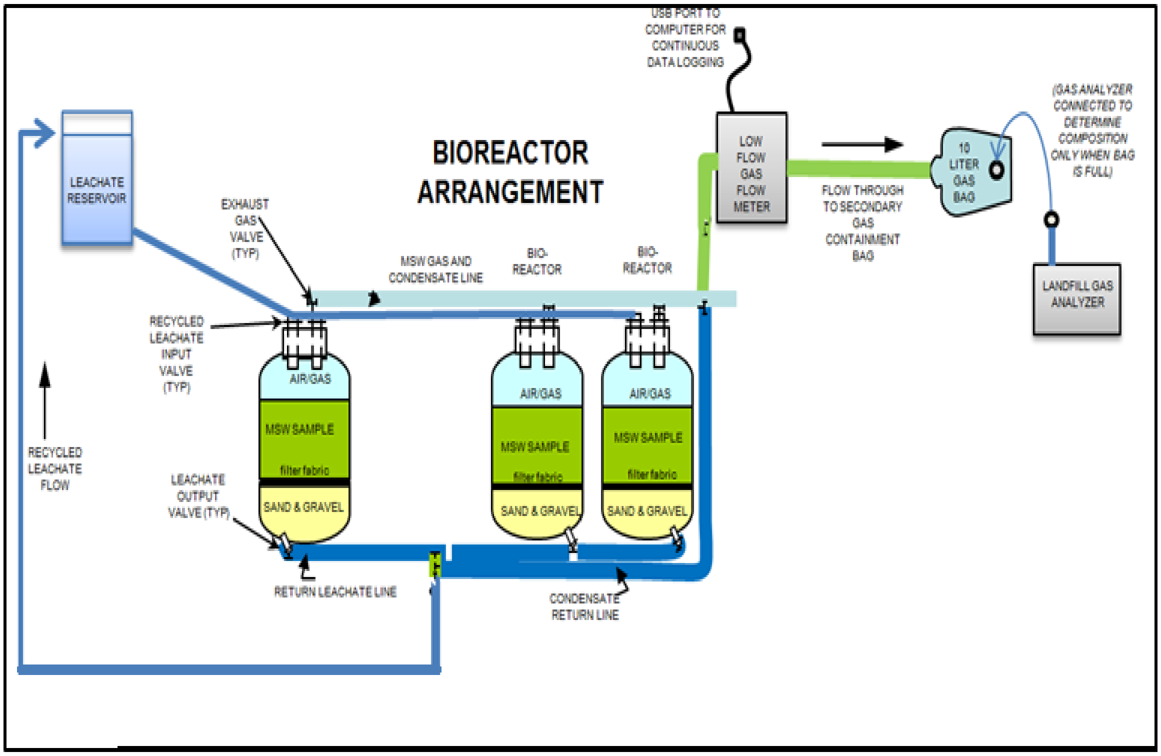

Figure 4.2 Bioreactor Arrangement Schematic

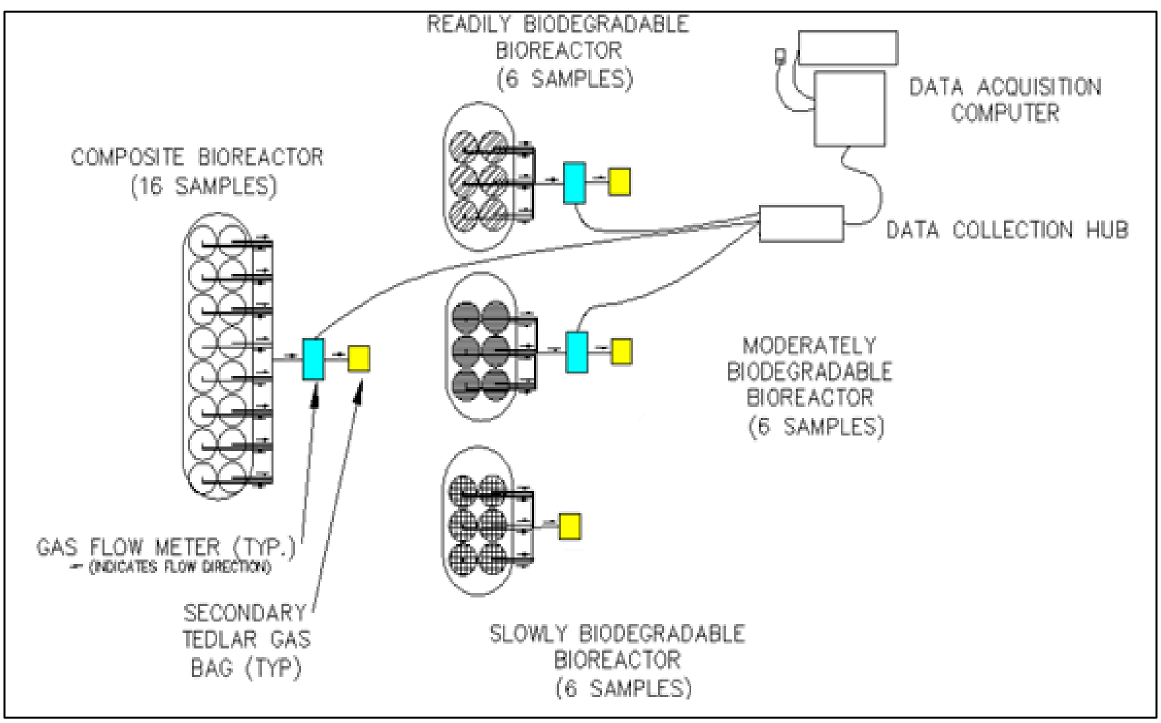

Figure 4.3 Gas Collection Arrangement

Figure 4.4 Bioreactor Test Set Up (Composite reactor tank shown)

Figure 4.5 Compression Test Equipment and Data Collection Hub Set Up

The four sets of bioreactors were established as follows:

- Bioreactor set 1 (16 total reactors): "Composite" - each of the constituents consisted of materials representative of mixed MSW. The composition of this mixture is contingent on regional variations. The author selected a composition representative for typical Northern New Jersey (United States) MSW for this study.

- Bioreactor set 2 (6 total reactors): "Readily Biodegradable" – constituents included materials which are **readily** biodegradable MSW, such as food waste and yard waste

- Bioreactor set 3 (6 total reactors): "Moderately Biodegradable" – constituents included materials which are **moderately** biodegradable MSW, including paper (newsprint, magazines, office paper, corrugated paper products) and wood chippings

- Bioreactor set 4 (6 total reactors): "Slowly Biodegradable" – constituents included materials which are **slowly** biodegradable MSW, including plastic and organic soil.

Compositions studies previously performed by PS&S were used to create the composition of MSW representative of Northern New Jersey. Table 4.1 indicates the relative proportion of each constituent in the composite sample. Figure 4.6 graphically depicts the constituent percentages of a combination of MSW, construction and demolition debris, and cover material typical of northeastern NJ landfills. This composition was utilized by others (Lifrieri 2010) and was specifically chosen to produce data which would allow for comparative analyses. Generally, components were separated into the categories of waste including: paper; wood; food; yard waste; textiles; glass; metal; plastic; and soil/miscellaneous and inert debris. Each bioreactor contained approximately 2.1 lb of combined constituent material.

Table 4.1 Constituents in a Typical Northeastern New Jersey Municipal Solid Waste

Constituent	Descriptor	Percentage [%]	Proportional Weight in Sample [lb]
Food	Readily	18.80	0.40
Yard Waste	Readily	6.30	0.13
Paper	Moderately	38.30	0.8
Textiles	Moderately	2.70	0.06
Wood	Moderately	2.10	0.04
Plastic	Slowly	12.50	0.26
Soil	Slowly	8.30	0.17
Glass	Inert	10.60	0.23
Metal	Inert	0.40	0.01
Totals		**100.00**	**2.10**

Source: PS&S, LLC Report to Bergen and Union County Utilities Authority (1993)

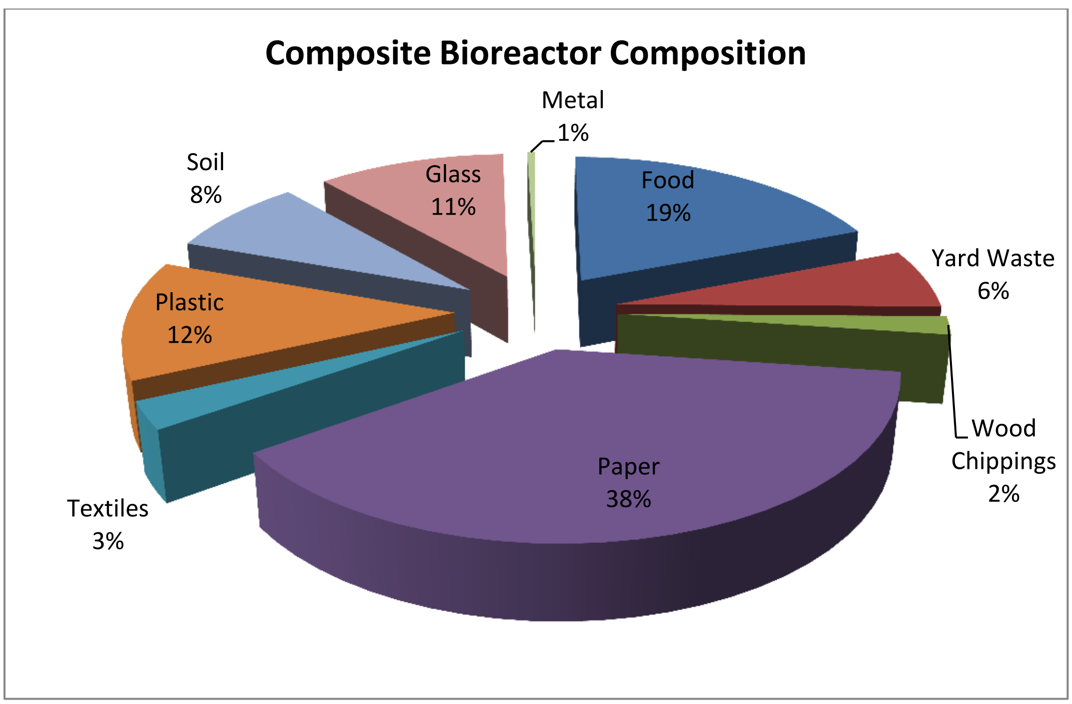

Figure 4.6 Composition of Typical Municipal Solid Waste in Northeastern New Jersey.
Source: PS&S, LLC Report To Bergen And Union County Utilities Authority (1993)

Individual reactors were comprised of components from one specific type of waste descriptor. The composition of readily, moderately, and slowly degradable reactors are indicated in Tables 4.2, 4.3, 4.4 and Figures 4.7, 4.8, 4.9, respectively.

Table 4.2 Constituents in "Readily Degradable" Bioreactors

Constituent	Descriptor	Percentage [%]	Proportional Weight in Sample [lb]
Food	Readily	76.20	1.60
Yard Waste	Readily	23.8	0.50
Totals		**100.00**	**2.10**

Table 4.3 Constituents in "Moderately Degradable" Bioreactors

Constituent	Descriptor	Percentage [%]	Proportional Weight in Sample [lb]
Paper	Moderately	88.60	1.86
Textiles	Moderately	6.70	0.14
Wood	Moderately	4.80	0.10
Totals		**100.00**	**2.10**

Table 4.4 Constituents in "Slowly Degradable" Bioreactors

Constituent	Descriptor	Percentage [%]	Proportional Weight in Sample [lb]
Plastic	Slowly	61.90	1.30
Soil	Slowly	38.10	0.80
Totals		**100.00**	**2.10**

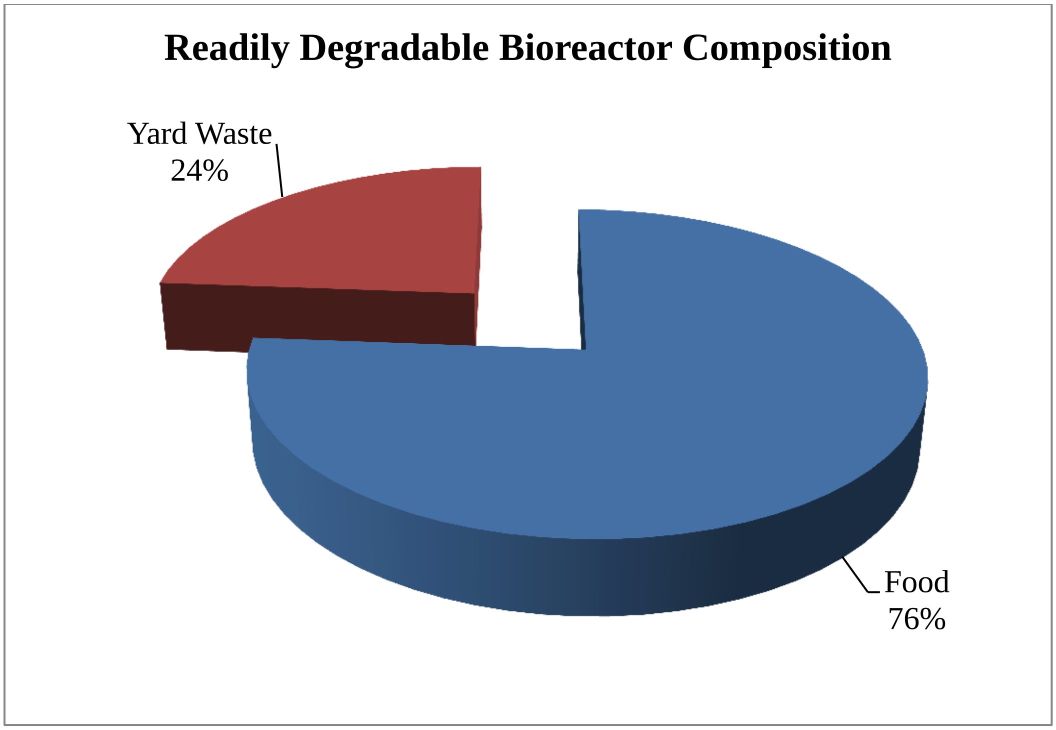

Figure 4.7 Composition of "Readily Degradable" Bioreactor Used for Testing

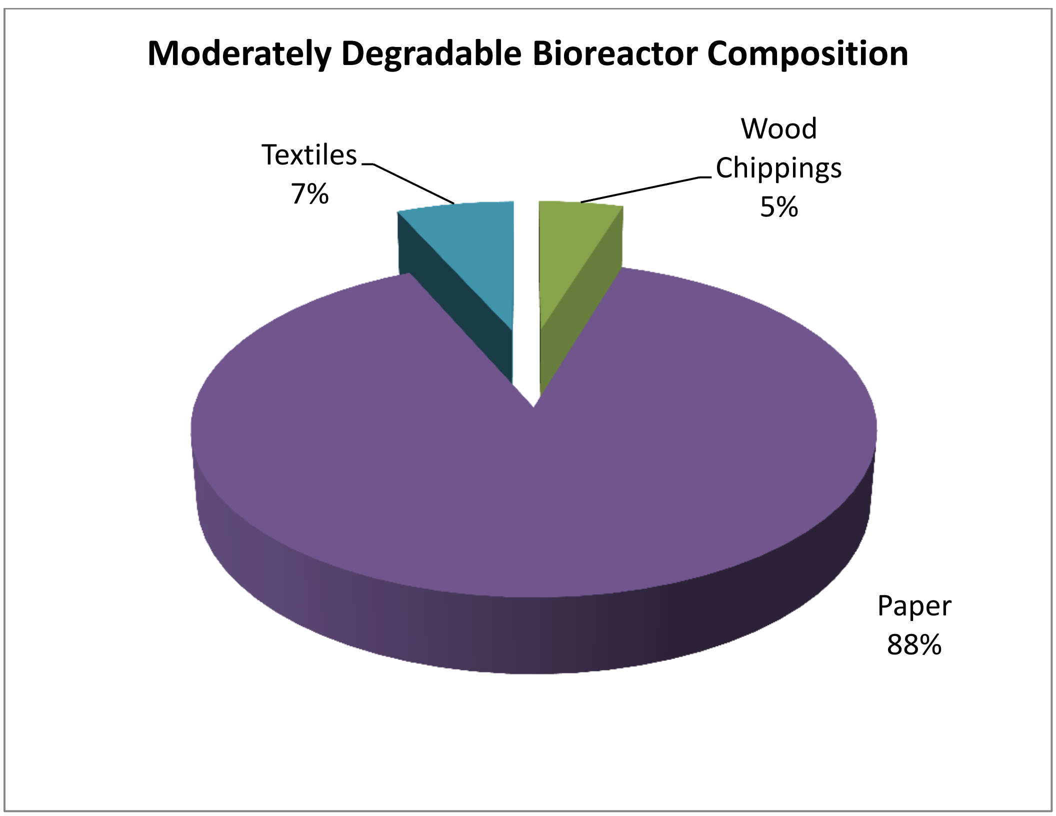

Figure 4.8 Composition of "Moderately Degradable" Bioreactor Used for Testing

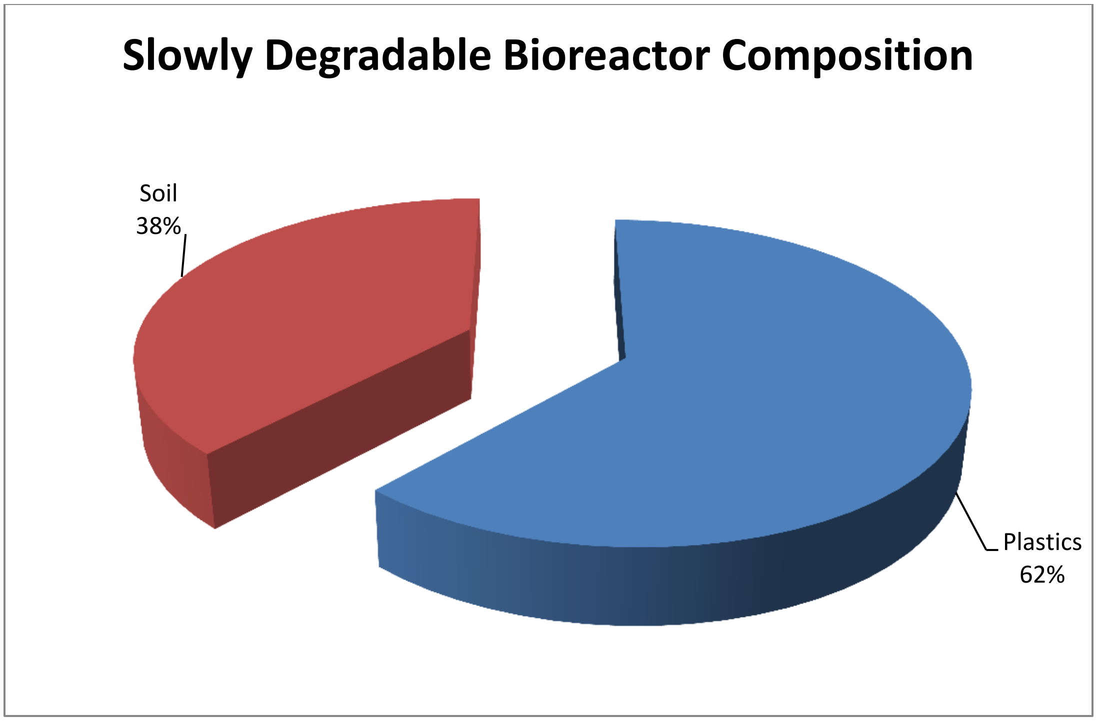

Figure 4.9 Composition of "Slowly Degradable" Bioreactor Used for Testing

The following materials were used during this work to simulate each waste:

- Yard Waste: grass, leaves, twigs mixture
- Food Waste: cooked ditalini (pasta)
- Wood: commercially-available pine wood for pet bedding
- Paper: mixture of finely-shredded office paper, newspaper, and craft paper
- Textiles: carpet shavings and finely-cut rags
- Plastic: commercial-available cylindrical (hollow) plastic beads
- Rubber: shredded rubber eraser
- Soil: topsoil from home improvement store
- Glass: crushed glass soda bottles (washed and cleaned prior to use)
- Metal: shavings and burrs from local auto shop

Samples were prepared for each bioreactor in accordance with the above distribution. All material was shredded, ground, and/or cut to fine particle sizes (maximum particle size less than ¼ inch) to increase surface area to promote decomposition.

Once sufficient quantities of material were obtained, the required mass of the constituent to fill each bioreactor was weighed and placed into zip-lock bags marked with bioreactor, sample number, and weight. Records for weights of each constituent comprising each of the 34 bioreactors are provided under Appendix A.1 – Bioreactor Assembly Records.

Constituents were assembled and mixed using a 5 liter zip-lock bag. Leachate was added to each sample to achieve a targeted moisture content of approximately 170 percent by weight to ensure leachate generation by exceeding the field capacity of the waste (Barlaz et.al 1989). Bags were rotated and shaken to mix constituents thoroughly. Moisture conditioning records are provided under Appendix A.2 - Moisture Conditioning Records. Moisture conditioned waste was then filled into the bioreactors in three equal lifts. Lift thickness was determined to create a waste density of approximately 40 to 50 pounds per cubic foot, representative of moderate to well-compacted waste (Tchobanglous 1993, Oweis and Khera 1998). Generally, lifts were placed between 1 inch to 1.5 inches thick and tamped 25 times per lift using a 5/8” diameter steel rod with 2 inch square plate attached to the tamping end.

A photo log depicting the above test set up and bioreactor assembly process has been provided as Appendix A.3 – Photo Log for Test Set Up.

Bioreactors were removed for destructive testing in accordance with the schedule provided as Table 4.5. The schedule was originally proposed using (C+H)/L testing as the basis and as discussed in the Proposal for Dissertation. Subsequently (C+H)/L testing was not utilized by this work as discussed in Chapter 5; however, the removal of bioreactors allowed for the determination of percent biodegradable mass with respect to time.

Table 4.5 Schedule for Removal of Bioreactors

Bioreactor Number	Date Removed	Time Since Start [days]
1	1/6/2014	49
2	1/19/2014	62
3	2/18/2014	92
4	3/20/2014	122
5	5/26/2014	189
6-16	9/1/2014	287

4.3 Data Collected and Maintenance of Records

Following assembly, bioreactors were submerged in a water bath maintained at a temperature of 110 ^{o}F to support enhanced biodegradation by mesophilic organisms (Tchobanoglous [1977], Barlaz, Ham and Schaefer [1989] and El-Fadil et al [1996], Lifrieri [2010]). Water bath temperatures maintained throughout the experiment are provided under Appendix B.1 – Water Bath Temperature Logs. Bioreactor tanks were covered with reflective-foil heat blankets to maintain temperature and restrict bioreactors from light to create a condition similar to waste buried in a landfill.

Gas collection piping was subsequently installed to connect gas flow from each reactor set in series to a dedicated measuring device. Gas produced from the composite bioreactor set and each readily, and moderately degradable reactors were collected using an automated gas flow meter (Sierra Instruments model MicroTrak 101) capable of providing instantaneous methane flow rate in standard cubic centimeters per seconds (sccm). A tedlar gas bag, manufactured by SKC and similar to those used by Lifrieri (2010) was connected in series after each gas flow meter to record total gas volume. A tedlar gas bag was connected directly to the slowly reactor set as an automated flow meter would not have sufficient sensitivity to register flows. Gas generation records maintained from gas flow equipment and gas bags have been provided as Appendix B.2 – Gas Volume (Methane) Readings from Gas Totalizer and Appendix B.3 – Gas Bag Records.

In addition to providing total gas produced the gas bags also allowed the ability to analyze gas composition over time and serve as a secondary check to the flow meters. Each of the gas meters were connected to a data collection hub via USB on a monthly basis to download daily gas production rates to a data acquisition computer. The required sensitivity range of the gas flow meter for this experiment was obtained by reviewing experimental results from Lifrieri (2010) who tabulated the gas generation rate of the bioreactor system on a 10 day basis. Generally, sensitivity was set between 0 to 30 sccm for composite and readily reactor sets, and 0 to 10 sccm for the moderately degradable reactor set. Sensitivity was also based on the weight of waste in each reactor set, which determined total gas production.

As gas was collected, a landfill gas meter (Landtec GEM2000+) was connected to the secondary gas collection bags periodically to understand the composition of the gas generated. The percentage of CH_4, CO_2, and O_2 was recorded. Gas composition records are provided under Appendix B.4 – Gas Composition Records.

To accelerate the on-set of biodegradation and simulate a bioreactor landfill, leachate was obtained from the Middlesex County Utilities Authority (MCUA) Middlesex County Landfill in East Brunswick, New Jersey. Leachate from this existing landfill was re-circulated as needed to maintain a moisture content of between 40 to 45 percent in bioreactors based on recommendations by USEPA (2003) and Reinhart and Townsend (1997). Moisture content was checked on a weekly basis using a PICO64 moisture content probe installed into one bioreactor representative of each of the four reactor sets. Non-destructive assessment of moisture content using the installed probe was required as taking a sample of waste to determine moisture content during the experiment would alter the gas production rate of the specific reactor, disrupt microorganism activity, and introduce oxygen into the system which would arrest the biodegradation process.

Leachate was added as needed to increase the moisture content of the waste sample to within the recommended limits. The procedure, schedule, and records for leachate injection are provided as Appendix B.5 – Moisture Content Meter Records. The frequent assessment and circulation of leachate to maintain this optimum was utilized to minimize spikes in gas production and create a more representative operation similar to landfills in practice. Leachate was MCUA Landfill in East Brunswick, New Jersey.

Chemical analyses conducted on the leachate have been provided under Appendix B.5.5 – Leachate Chemical Analyses Test Results. Prior to injection of leachate, the leachate was warmed by submerging the leachate container in the water bath to ensure like-temperatures when introducing into the bioreactors.

As indicated in the test schedule, one bioreactor was decommissioned from the composite reactor to be sampled for (C+H)/L testing and used for compression testing for compressive characteristics of the waste at the determined biodegradation ([C+H]/L) state. During decommissioning, the waste sample was removed from the bioreactor, mixed to ensure homogeneity, and split into five equal parts. Two parts were processed by removing plastics and synthetics from the sample to be sent to Dr. Morton Barlaz at North Carolina State University for (C+H)/L testing. These constituents were removed as it was shown plastic and synthetic constituents do not dissolve in 72 percent w/w sulfuric acid and would artificially increase the lignin content of the sample as a result. The use and limitations of (C+H)/L for the purposes of this experiment are further discussed in Chapter 5. Of the remaining three parts of waste, two parts were used for compression testing and one part was frozen for redundancy and contingency future testing, as required.

Samples were prepared for consolidation testing by mixing each waste to ensure uniform moisture content, then filling the sample within the consolidometer ring in lifts. Lifts were placed in approximately 1/4 inch loose lifts (approximately one tablespoon per lift) and were tamp-compacted using a hard rubber stopper with a 2.45 inch diameter placed on the sample and struck seven times with a 3.5 lb cylindrical weight dropped from a height of approximately one inch. This procedure was repeated until a final compacted height of one inch was obtained. Minor cosmetic trimming and patching was completed to create a uniform and flat sample surface for testing (Lifrieri 2010).

After compaction, samples were subsequently placed in a fixed ring consolidation cell manufactured by Humboldt and were tested using table-top mounted dead-weight consolidation equipment. Dial gage reading data was recorded electronically at pre-determined time intervals using Humboldt HTMS logging software. Compression tests were performed in general accordance with ASTM D2435 – Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading (ASTM 2011).

Samples were allowed to consolidate at pressure increments of 0.137 ton per square foot (tsf), 0.275 tsf, 0.550 tsf, 1.10 tsf, and 2.20 tsf for a period of 24 hours. A pressure of 4.40 tsf was applied and maintained following the 2.20 tsf pressure increment for a minimum period of two months or until it was observed that sample reached the stage of biodegradation, characterized by an increase in the strain rate (C_β). Load parameters for the samples to simulate self-weight and applied loads of landfills of variable heights were computed from resulting data. Compression parameters (C'_c, C_α, and C_β) were determined at the specific states of decomposition observed from testing. Rationale for the selected load increments are based on those used by Lifrieri (2010).

Samples were placed into the consolidometer and removed in accordance with the schedule shown in Table 4.6. Additional details regarding the test set-up, procedure, and records from initial and final consolidation tests are provided under Appendix C – Consolidation Test Results. Tests were suspended once the biodegradation phase of the compression parameter could be ascertained.

Table 4.6 Compression Test Schedule

Test	Bioreactor Number	Date Started	Date Finished	Duration [days]
C-1-1	1	1/6/2014	7/27/2014	202
C-1-2	1	1/6/2014	7/27/2014	202
C-2-1	2	1/19/2014	5/29/2014	130
C-2-2	2	1/19/2014	5/29/2014	130
C-3-1	3	2/19/2014	5/30/2014	100
C-3-2	3	2/19/2014	5/30/2014	100
C-4-1	4	3/20/2014	7/23/2014	125
C-4-2	4	3/20/2014	7/23/2014	125
C-5-1	5	4/12/2014	7/31/2014	125
C-5-2	5	4/12/2014	7/31/2014	125
C-Final-1	6	9/1/2014	11/16/2014	76
C-Final-2	6	9/1/2014	11/16/2014	76

Following completion of the experiment, remaining operational bioreactors were decommissioned after performing a series of measurements. The intent of the measurements was to understand the change in density and loss of mass which may be attributable to biodegradation. The thickness of the remaining waste mass was measured, along with moist weight of the waste to determine final in-situ density. Records from bioreactor decommissioning at end of the experiment are provided as Appendix B.7 – End of Test Bioreactor Decommissioning Records.

Equipment used for measurement and testing were calibrated as per manufacturer recommendations to ensure accuracy during the testing process. Calibration records for equipment used for this work are provided under Appendix D – Calibration Records for Measuring Devices.

The author created example instructions and forms to provide repeatability of the method used for this work and future works. Example instructions and forms used by author to guide establishment of bioreactors are included under Appendix E.1 – Work Plan and Testing Instructions and E.2 – Standard Forms Used for Commissioning Bioreactors and Test Equipment. Recognizing the sensitivity of the microorganisms controlling the biodegradation process, it was imperative that the required temperature was maintained, and continuous records for gas production and compression testing also be maintained. The author created an Emergency Workplan which was employed during the experiment and included as Appendix E.3 – Emergency Workplan. A list of parts to construct the test set up and bioreactors has also been included as Appendix E.4 – Parts List.

CHAPTER 5

RESULTS OF LABORATORY PROGRAM

The following chapter presents data collected over a period of approximately 260 days by the laboratory program discussed in Chapter 4. Gas production by two methods, primary flow meter and secondary tedlar gas collection bags, compressibility parameters by consolidometer apparatuses, and other physical and engineering parameters which were measured and observed are discussed below.

5.1 Methane Gas Data Collected from Flow Meters

As indicated in Section 4.3, methane gas produced from the composite, readily, and moderately degradable reactors sets were metered using a MicroTrak 101 automated gas flow meter manufacturer by Sierra Instruments. Each of the gas meters was connected to a data collection hub via USB on a monthly basis to download daily gas production rates to a data acquisition computer.

Tables B.2.1 through B.2.3 in Appendix B present the complete data recorded on a daily basis, at minimum, by methane gas flow meter for the respective composite, readily, and moderately degradable sets. Table 5.1 below provides an excerpt from the Appendix tables indicating the data which was recorded from the meters. The table shows date, time, and cumulative days since start the instantaneous flow meter reading was recorded. Using the weight of bioreactors obtained from commissioning record, the observed flow reading normalized to by pound of waste is computed.

The columns titled "CH_4 Remaining" and " % of Theoretical Total" were based on a calculated theoretical total gas production of 6.23, 9.04, and 8.43 cubic feet per pound waste for composite, readily, and moderately degradable bioreactor sets, respectively. Calculations for theoretical total gas quantity were conducted using the Lambda method of gas production as modified by Lifrieri (2010) and detailed in Chapter 3. Based on the stoichiometric relationship it is predicted that methane comprised 55% of the total gas; therefore theoretical total methane gas volumes of 3.43, 4.97, and 4.64 cubic feet per pound waste were used to assess the methane remaining and percent of total theoretical remaining and for evaluating the cumulative production from flow meters.

Figure 5.1 and 5.2 illustrate gas production on a daily basis as recorded by the gas flow meter and cumulative gas production, respectively, for the composite bioreactor set. Gas production rate and cumulative gas production are normalized and reported per pound of waste in the bioreactor set.

Figure 5.3 and 5.4 illustrate daily gas production and cumulative gas production per pound waste, respectively, for the readily bioreactor set. Similarly Figure 5.5 and 5.6 illustrate daily gas production and cumulative gas production per pound waste, respectively, for the moderately degradable bioreactor set. No flow meter was connected to the slowly degradable bioreactor set as the automated flow meter would not have sufficient sensitivity to register flows. A tedlar gas bag connected directly to the slowly degradable reactor set was subsequently used. Data from the tedlar gas bags is provided and discussed later. Total gas collection by secondary tedlar gas bags is discussed in Section 5.2.

Table 5.2 summarizes data collected from the gas flow meters for composite, readily, and moderately degradable bioreactor sets. The "Estimated Total Gas Produced at End" is provided based an estimated 55% of methane gas with respect to total gas.

Table 5.1 Excerpt of Data Recorded from Composite Methane Gas Flow Meter

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Weight in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
1/22/14	14:00	65	10.44	23.89	0.44	0.022	2.05	40%
1/23/14	8:00	66	10.31	23.89	0.43	0.022	2.04	40%
1/24/14	8:00	67	10.41	23.89	0.44	0.022	2.02	41%
1/25/14	8:00	68	10.83	23.89	0.45	0.023	1.99	41%
1/26/14	8:00	69	9.31	23.89	0.39	0.020	1.97	42%
1/27/14	8:00	70	9.51	23.89	0.40	0.020	1.95	43%
1/28/14	8:00	71	9.27	23.89	0.39	0.020	1.93	43%
1/29/14	21:00	72	8.71	23.89	0.36	0.019	1.90	44%
1/30/14	20:00	73	8.60	23.89	0.36	0.018	1.89	44%
1/31/14	20:00	74	8.87	23.89	0.37	0.019	1.87	45%
2/1/14	19:00	75	8.61	23.89	0.36	0.018	1.85	46%
2/2/14	9:00	76	8.75	23.89	0.37	0.019	1.84	46%
2/3/14	8:00	77	8.76	23.89	0.37	0.019	1.82	46%
2/4/14	8:00	78	8.51	23.89	0.36	0.018	1.80	47%
2/5/14	21:00	79	7.27	23.89	0.30	0.015	1.78	48%

Note: Tables B.2.1 through B.2.3 in Appendix B present complete data for all meters

5.1.1 Methane Gas Data Collected from Composite Flow Meter

Data collected from the flow meter used for composite waste indicated a peak rate of 0.035 cubic feet of methane per pound waste occurred 41 days into the experiment. Integration of the gas production curve resulted in approximately 2.465 cubic feet of methane per pound waste collected over a 221 day period. Based on a total theoretical methane potential of 3.43 cubic feet per pound waste calculated by the lambda method, approximately 72 percent of the potential was captured at conclusion of the experiment. Using a proportion of 55 percent methane comprising total gas, a total of 4.48 cubic feet of total gas is anticipated to have been produced.

Secondary gas bags measuring total volume, however, indicate 5.33 cubic feet of total gas were collected. The author explains this 16 percent deviation between methods as a result of trace landfill gases produced during early phases of decomposition, and the generalization that the proportion of gas remained constant at 55 percent methane throughout the experiment. However, the proportion of methane may fluctuate depending on the phase of biodegradation the waste is undergoing, as discussed in Chapter 2. Gas flow meters also provided a more accurate measurement of gas production in comparison to the secondary gas bags, which are based on a visual interpretation of the capacity of the bag and therefore subject to variation.

It can be observed from the Figure 5.1 that an 11 day lag exists prior to the start of data readings. As gas production occurs in several phases, the author notes that initial phases of decomposition were occurring during this period and other landfill gases may have been developing. Since gas flow meters are calibrated against methane, the author believes that data could be not registered for this period. However, this volume of gas was not overlooked during the experiment and was captured by the secondary gas bags which determine the total gas, and therefore the volume added by non-methane gases.

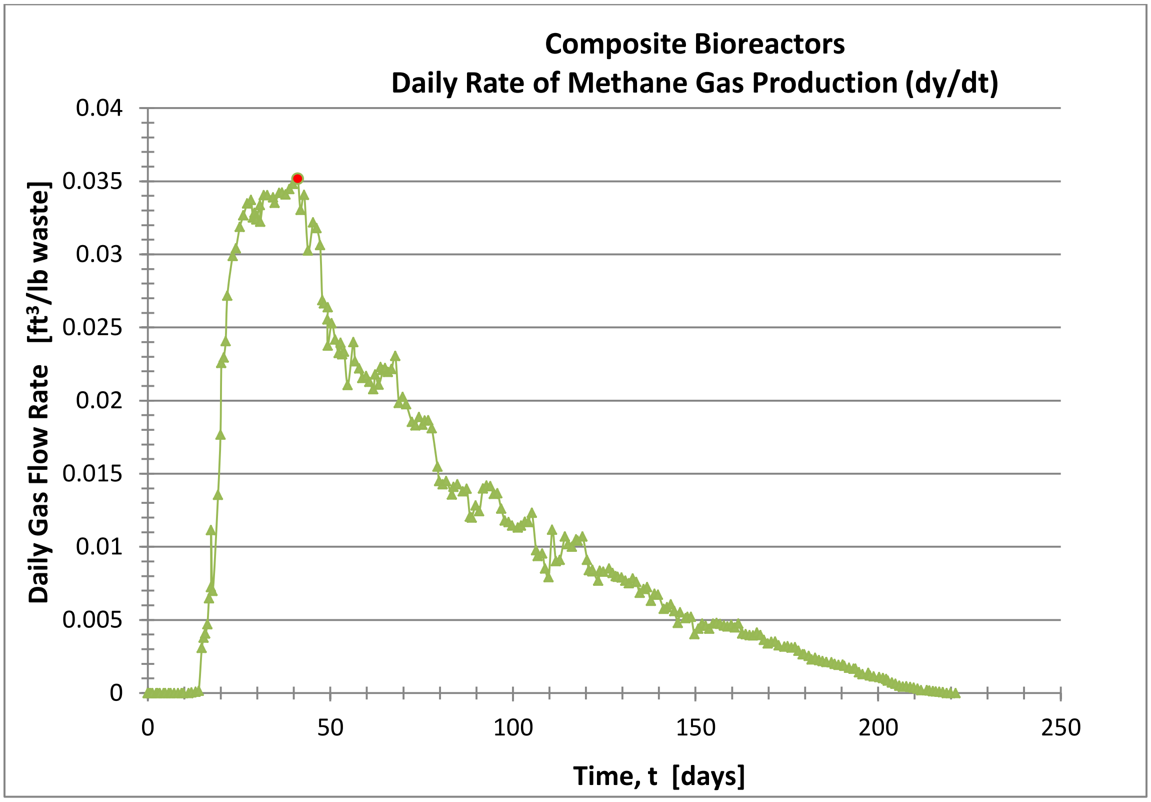

Figure 5.1 Daily Volume of Methane Gas Produced from Composite Flow Meter

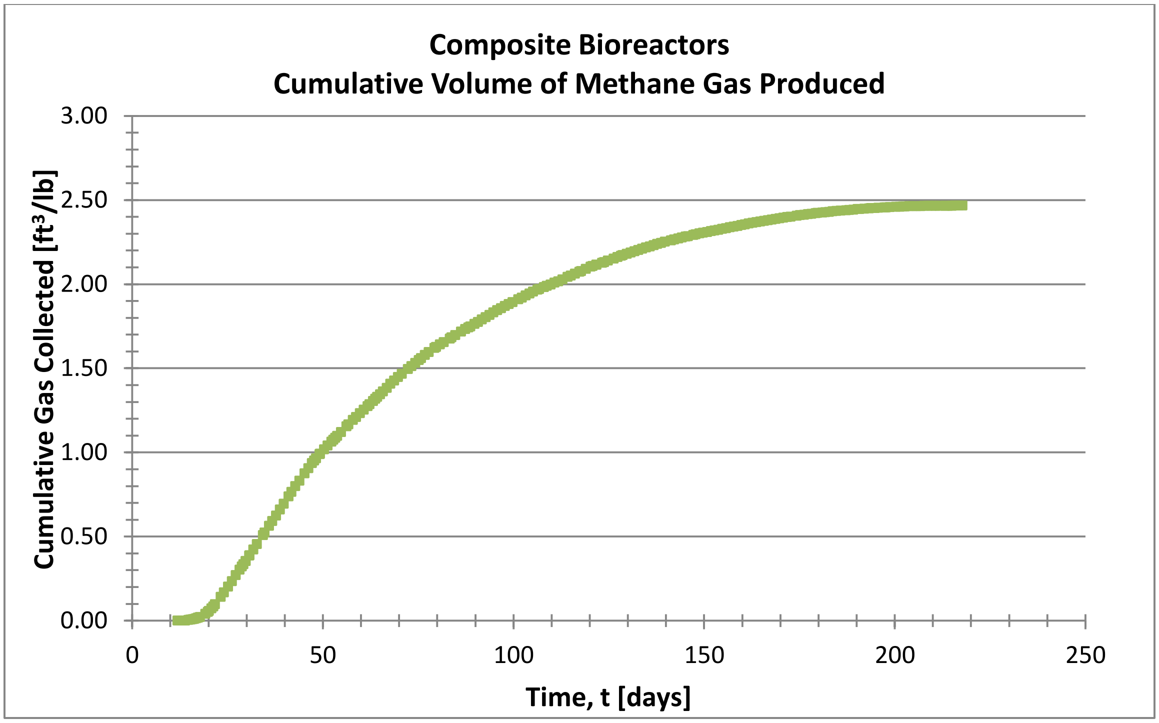

Figure 5.2 Cumulative Volume of Methane Gas Produced from Composite Flow Meter

5.1.2 Methane Gas Data Collected from Readily Degradable Waste Flow Meter

Data collected from the flow meter used for readily degradable waste indicated a peak rate of 0.114 cubic feet of methane per pound waste occurred 23 days into the experiment. It is observed that the on-set of methane gas production occurs earlier than that for the composite bioreactor. This can be attributed to the contents of the readily degradable bioreactor being constituents which are rapidly degradable. Integration of the readily degradable gas production curve resulted in approximately 4.623 cubic feet of methane per pound waste collected over a 221 day period.

Based on a total theoretical methane potential of 4.97 cubic feet per pound waste calculated by the Lambda method, approximately 93 percent of the potential was captured at conclusion of the experiment. Using a proportion of 55 percent methane comprising total gas, a total of 8.41 cubic feet of total gas is anticipated to have been produced. Secondary gas bags measuring total volume indicate 8.88 cubic feet of total gas were collected, therefore the author notes good agreement between the two methods. The additional volume collected by the secondary gas is likely attributable to the production and capture of trace landfill gases produced during early phases of decomposition.

Similar to the composite bioreactor, a 5 day lag exists prior to the start of methane gas flow readings. The author suggests that, as the waste is readily decomposable, the initial phases of decomposition may have occurred as early as during the time the wastes were batched and stored prior to filling into bioreactors. As the initial phases are driven by aerobic conditions, these conditions exist during initial batching and storage of samples and may allow the waste to complete this stage of decomposition prior to the start of the experiment. An inspection of the curve indicates that 50 percent of the theoretical gas was captured by day 50 of the experiment, with 90 percent of theoretical gas captured after day 119. Gas collection was stagnant after approximately this date.

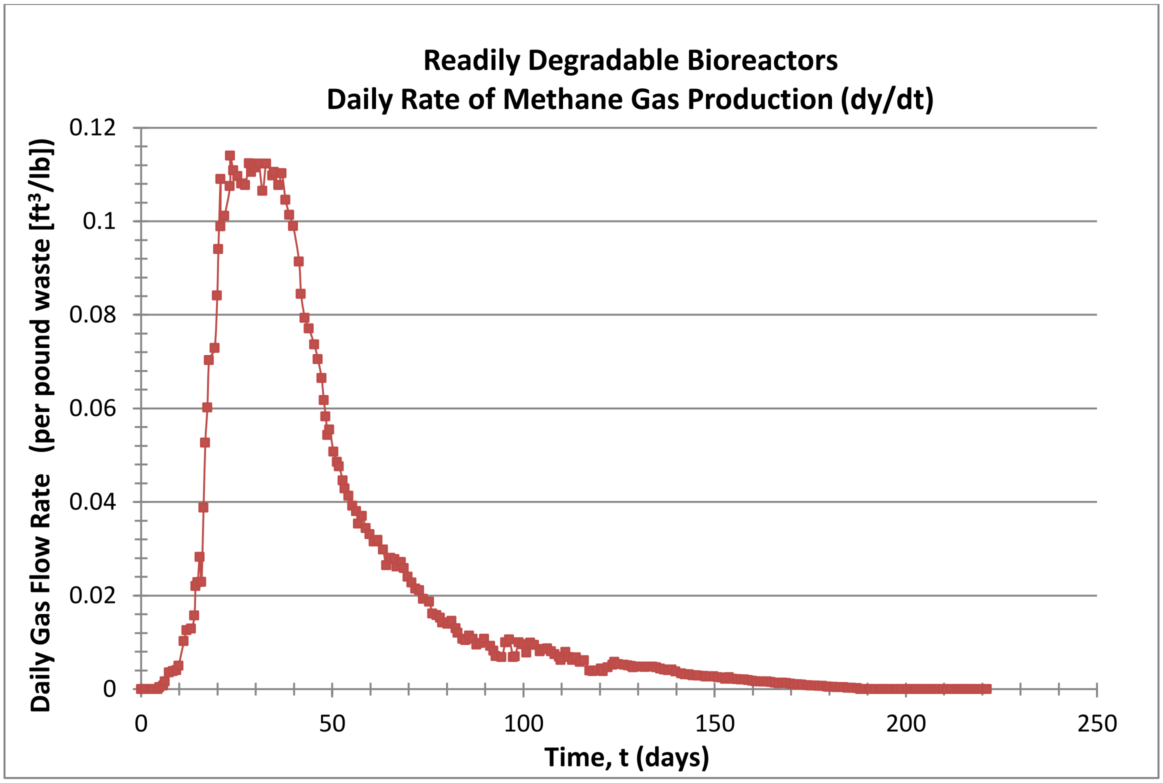

Figure 5.3 Daily Volume of Methane Gas Produced from Readily Degradable Flow Meter

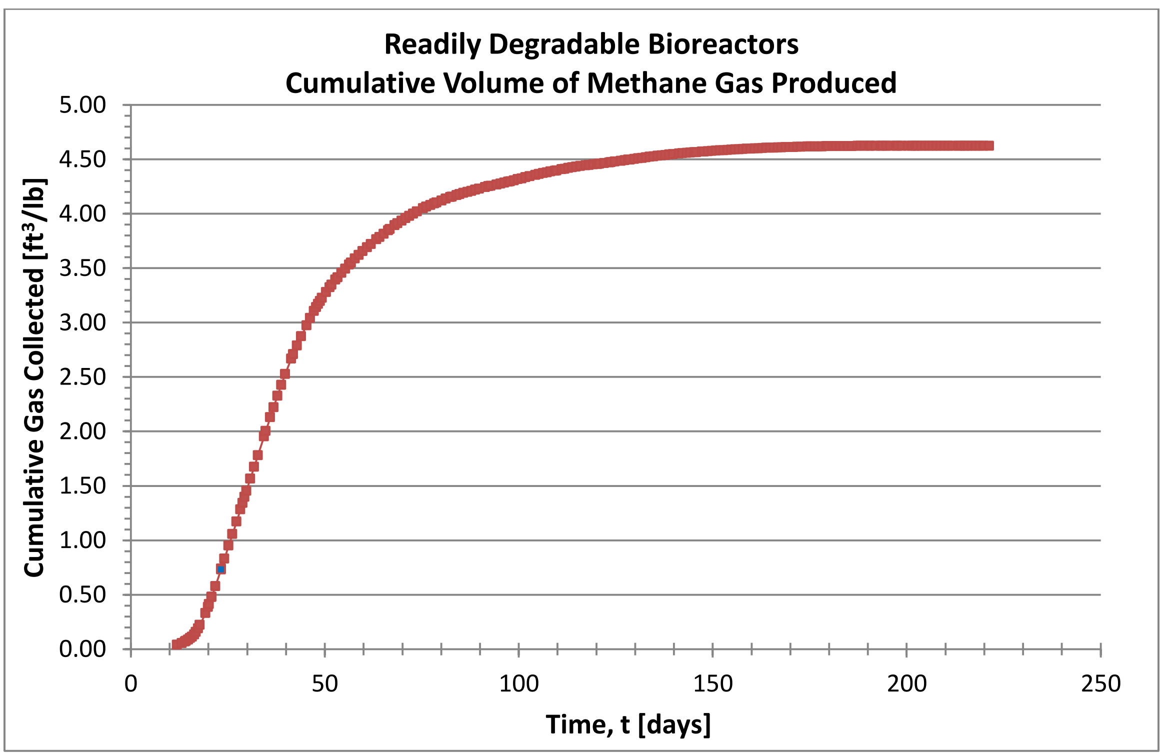

Figure 5.4 Cumulative Volume of Methane Gas Produced from Readily Degradable Flow Meter

5.1.3 Methane Gas Data Collected from Moderately Degradable Waste Flow Meter

Data collected from the flow meter used for moderately degradable waste indicated a peak rate of 0.034 cubic feet of methane per pound waste occurred 80 days into the experiment. It is observed that the on-set of methane gas production occurs later than both the readily degradable and composite bioreactor. This is expected as the readily degradable bioreactor contained constituents such as food and yard waste which are more easily biodegradable than wood chippings, paper, and textiles of the moderately degradable waste. Likewise, as the composite bioreactor contains readily biodegradable constituents, it is anticipated that gas production from these components will occur before the moderately decomposable wastes such as those comprising the moderately degradable bioreactor set.

Integration of the moderately degradable gas production curve resulted in approximately 2.860 cubic feet of methane per pound waste collected over a 261 day period. Gas collection for the moderately bioreactor was maintained for a period longer than others since observable gas flow was occurring as witnessed by the filling of secondary tedlar bags, although the primary flow meter did not register flow. Based on a total theoretical methane potential of 4.64 cubic feet per pound waste calculated by the lambda method, approximately 62 percent of the potential was captured at conclusion of the experiment. Using a proportion of 55 percent methane comprising total gas, a total of 5.20 cubic feet of total gas is anticipated to have been produced. Secondary gas bags measuring total volume indicate 5.80 cubic feet of total gas were collected, therefore the author notes good agreement between the two methods.

The additional volume collected by the secondary gas is likely attributable to the production and capture of trace landfill gases produced during early phases of decomposition.

Similar to the other bioreactors, a 20 day lag exists for the moderately degradable bioreactor set prior to the start of methane gas flow readings. An inspection of the curve indicates that 50 percent of the theoretical gas was captured by day 134 of the experiment, with 62 percent of theoretical gas captured after day 219. Gas collection was nearly stagnant based on information from both the flow meter and secondary tedlar bags after approximately this date. The author comments that the observable spikes in data occur two to three days after leachate has been recirculated or added in the bioreactors.

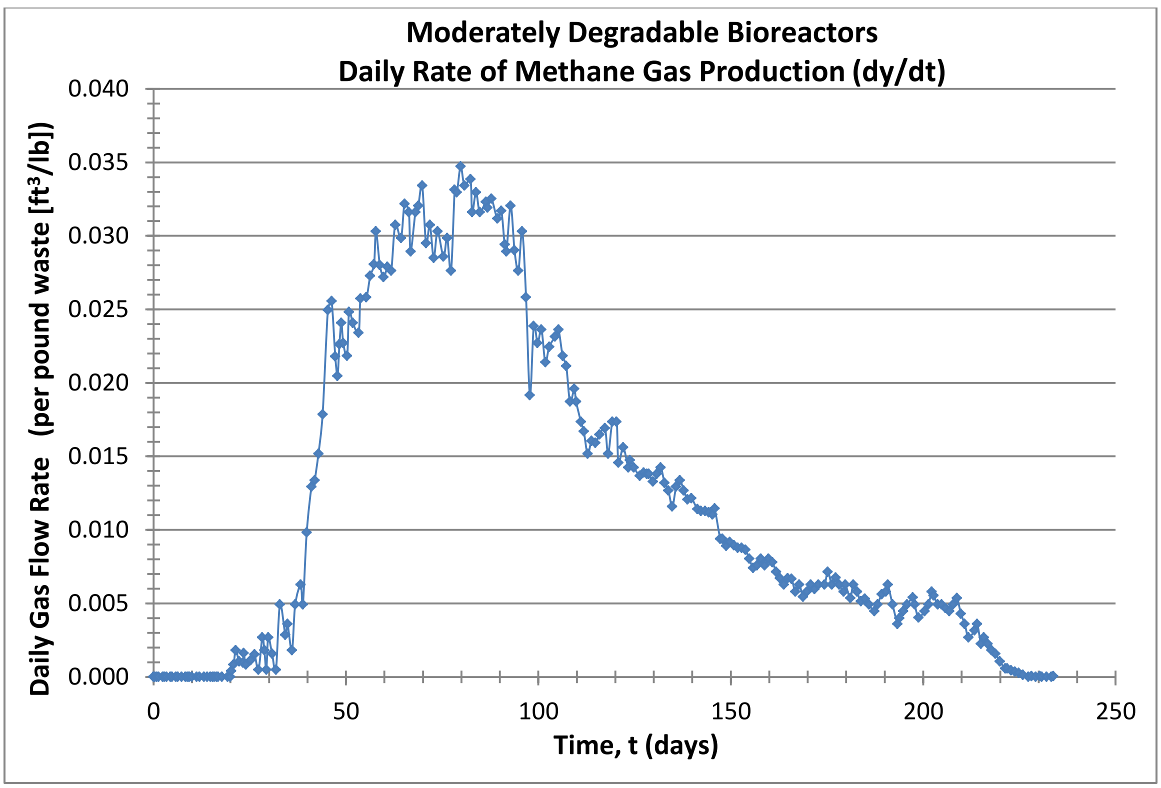

Figure 5.5 Daily Volume of Methane Gas Produced from Moderately Degradable Flow Meter

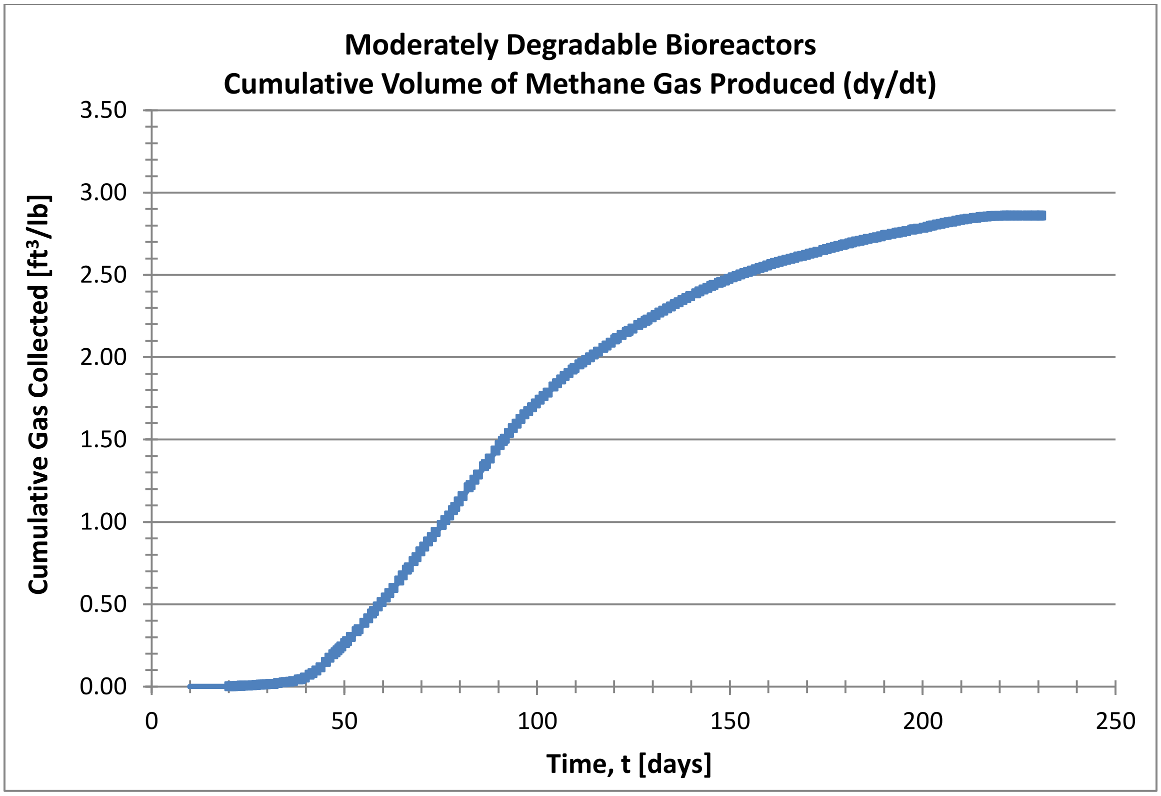

Figure 5.6 Cumulative Volume of Methane Gas Produced From Moderately Degradable Flow Meter

Toward the end of the experiment, the author observed that the pressure through each of the gas flow meters was less than 1 pound per square inch on several occasions. As the flow meters require a minimum pound per square inch pressure across the meter to register flow accurately, it is suggestd that a spike would occur once the minimum pressure differential was achieved and the flow meter recorded data. These spikes are more distinguishable toward the end of gas collection.

Table 5.2 Summary of Data Collected by Gas Flow Meters

Reactor Set	Max Daily Methane Flow Rate [(ft^3/lb)/day]	Day Since Start for Max Reading	Days Until Start of Methane Flow Readings	Cumulative Volume Methane at End [ft^3/lb]	Estimated Total Gas Produced at End [ft^3/lb]
Composite	0.035	41	11	2.645	4.809
Readily	0.114	23	5	4.623	8.405
Moderately	0.034	80	20	2.860	5.200

5.2 Total Gas Data Collected from Tedlar Gas Bags

Gas bags were utilized during the experiment to serve as a secondary check to the flow meters and allow for characterization of gas composition at periodic intervals over time. It should be noted that the tedlar gas bags reported and collected the total gas collected, irrespective of gas composition, as opposed to gas flow meters which were calibrated for use with methane gas and provided daily methane gas flow rate.

The use of tedlar bags is discussed in Chapter 3. Various capacity bags were used, including 1 liter, 10 liter, and 50 liter bags, depending on the volume of flow anticipated. Lower capacity bags were used at the beginning and end of the experiment to capture the gas as it was emitted at lower flow rates and lower resulting sample volumes. Tables B.3.1 through B.3.3 in Appendix B present the complete data recorded for secondary gas bags used in series after gas flow meters for composite, readily, and moderately degradable bioreactor sets. Table B.3.4 tabulates records for gas bags used as the primary means of establishing volume of total gas produced by the slowly degradable bioreactor set. Figure 5.7 illustrates the manufacturer's recommendation for inflation.

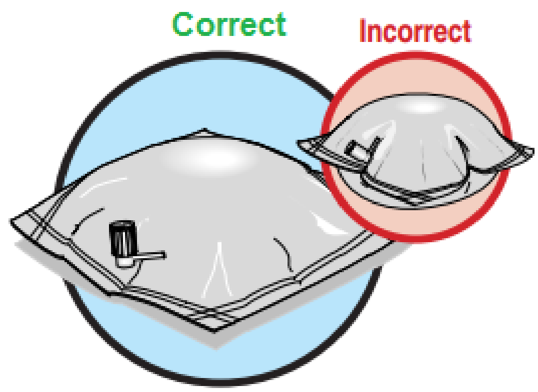

Figure 5.7 Manufacturer's (SKC) recommendation for inflation of gas bags

Table 5.3 provides an excerpt from the Appendix tables indicating the data which was recorded from the gas bags. The table shows date, time, and cumulative days since start and the date the gas bag was changed. Columns titled "Bag Volume" and "Actual Bag Volume" are based on manufacturer recommendations, which indicated that proper inflation of the gas bag would result in 80 percent of the rated total capacity. Therefore, proper inflation would result in gas bag volumes of 0.8, 8, and 40 liters, respectively.

In select circumstances, the rate of gas production did not allow a full bag to be swapped out for an empty bag causing this recommendation to be exceeded and be filled to total rated capacity. These occurrences were noted, and the total rated capacity of the bag was used. Using the weight of bioreactors obtained from commissioning record, the observed flow reading normalized to by pound of waste is computed. The equivalent average daily flow rate was obtained by taking the actual bag volume of the tedlar bag used and dividing by the time, in days, since the previous gas bag swap.

Table 5.3 Excerpt of Data Recorded for Tedlar Gas Bags – Composite Bioreactors

Gas Flow Meter Readings - Composite Flow Meter									
Date	**Dry Weight Waste**	**Cumulative No. of Days**	**Bag Volume**	**Actual Bag Volume**	**Cumulative Volume of Gas [L]**	**Cumulative Volume of Gas [ft^3]**	**Cumulative Volume of Gas per LB Waste [ft^3/lb]**	**Average Daily Volume (ft^3/day)**	**Average Daily Flow Rate [ft^3/lb]**
11/27/2013	27.32	9	1	0.8	0.8	0.038	0.001	0.004	0.000
12/2/2013	27.32	14	50	40	40.8	1.914	0.070	0.375	0.014
12/5/2013	27.32	17	50	40	80.8	3.790	0.139	0.625	0.023
12/7/2013	27.32	19	50	40	120.8	5.667	0.207	0.938	0.034
12/8/2013	27.32	20	50	40	160.8	7.543	0.276	1.876	0.069
12/9/2013	27.32	21	50	45	205.8	9.654	0.353	2.111	0.077
12/10/2013	27.32	22	50	40	245.8	11.531	0.422	1.876	0.069
12/11/2013	27.32	23	50	30	275.8	12.938	0.474	1.407	0.052
12/12/2013	27.32	24	50	30	305.8	14.345	0.525	1.407	0.052
12/13/2013	27.32	25	50	40	345.8	16.222	0.594	1.876	0.069
12/14/2013	27.32	26	50	40	385.8	18.098	0.662	1.876	0.069
12/15/2013	27.32	27	50	40	425.8	19.975	0.731	1.876	0.069
12/16/2013	27.32	28	50	45	470.8	22.086	0.808	2.111	0.077
12/17/2013	27.32	29	50	40	510.8	23.962	0.877	1.876	0.069
12/17/2013	27.32	29.5	50	40	550.8	25.839	0.946	3.753	0.137
12/18/2013	27.32	30	50	40	590.8	27.715	1.014	3.753	0.137
12/18/2013	27.32	30.5	50	40	630.8	29.592	1.083	3.753	0.137
12/19/2013	27.32	31	50	40	670.8	31.468	1.152	3.753	0.137
12/19/2013	27.32	31.5	50	40	710.8	33.345	1.221	3.753	0.137

Note: Tables B.3.1 through B.3.3 in Appendix B list complete gas bag data for all sets

5.2.1 Total Gas Data Collected from Composite Tedlar Bags

For comparison to work completed by Lifrieri (2010), Figure 5.8 graphically depicts gas production on a 10-day basis as averaged and obtained by tedlar gas bag record for the composite bioreactor set. Figure 5.9 depicts cumulative gas production as noted by actual gas bag volume and dates since start of the experiment. Both gas production rate on a 10-day basis and cumulative gas production are presented normalized and reported per pound of waste in the bioreactor set. Figures 5.10 and 5.11, Figure 5.12 and 5.13, and Figure 5.14 and 5.15 graphically depict similar data for the readily, moderately, and slowly degradable bioreactor sets, respectively.

Data collected from the tedlar gas bags connected to the composite bioreactor set indicated a peak 10-day volume of 1.373 cubic feet of total gas per pound waste occurring approximately 30 days into the experiment. Summation of the actual gas bag volumes for all bags used indicated approximately 5.332 cubic feet of total gas per pound of waste were collected over a 221 day period. Based on a total theoretical methane potential of 6.23 cubic feet per pound waste calculated by the lambda method, approximately 85 percent of the total potential was captured by gas bags connected to the composite bioreactor set at conclusion of the experiment.

Prior work completed by Lifrieri (2010) used data collected by gas bags to characterize the different waste types as regions of the gas collection curve. Four time-dependent regions by visual inspection were established: a linear portion from the start of the work to time of maximum gas production (t_1); the readily biodegradable region (t_2); the moderately biodegradable region (t_3); and, the slowly biodegradable region.

The regions occurred between 0 days and 35 days, 35 days to 60 days, 60 days to 270 days, and 270 days and onward for the respective regions. Individual, "k_n" decay constants similar to those suggested by Findikakis et al. (1979) were obtained by Lifrieri from an exponential best-fit curve approximation for the readily, moderately, and slowly biodegradable regions. Table 5.4 presents a comparison of the work completed by Lifrieri (2010) and the work completed herewith.

Reviewing the differences between data, it is suggested maintaining an optimum moisture content of approximately 45 percent (leachate recirculation), enhanced gas collection equipment and method, and operating the reactors similar to a bioreactor landfill accelerates the rate of gas production. As seen by the data, each of the regions of decomposition occur earlier in the work completed by this author, with greater decay constants which generally correlate to more rapid rates of decomposition. The maximum 10-day flow rate of 0.4 cubic feet of total gas per pound waste observed by Lifrieri (2010) compared to maximum 10-day flow rate of 1.373 cubic feet of total gas per pound waste observed by this author further corroborate this hypothesis.

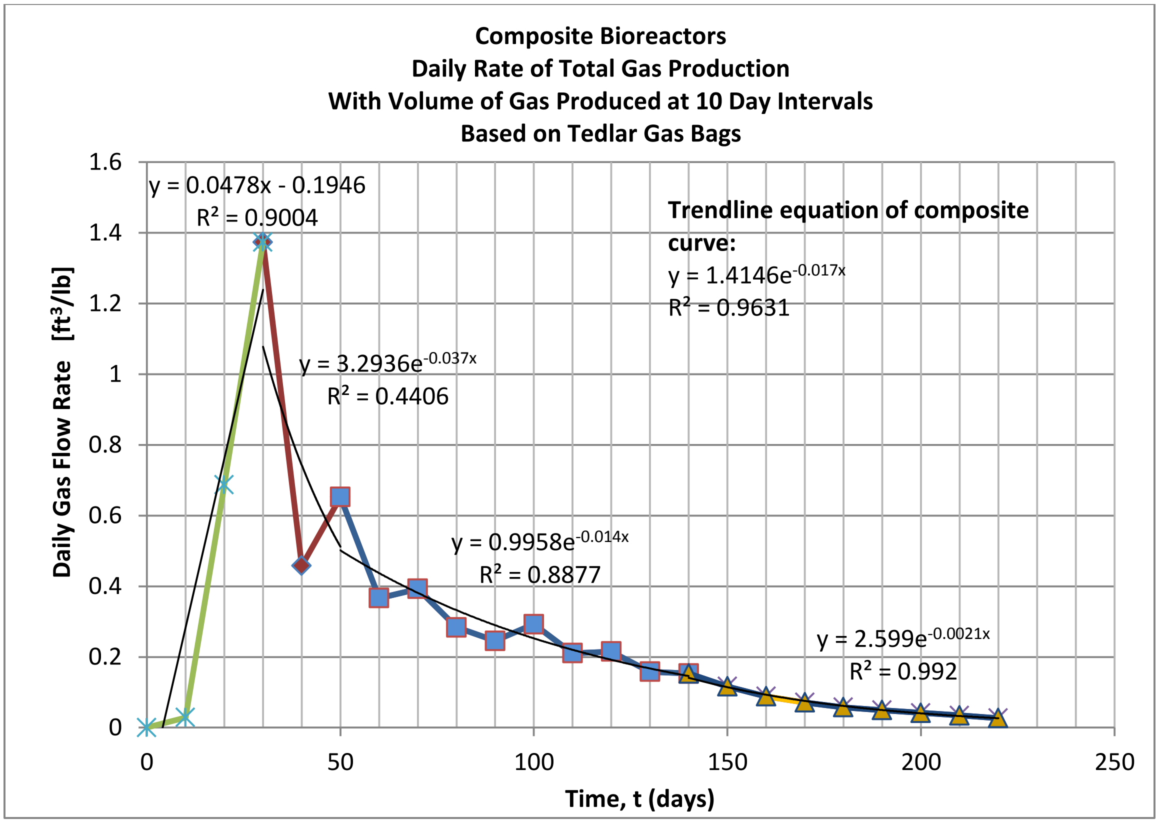

Figure 5.8 Daily Volume of Total Gas Produced From Composite Tedlar Bags

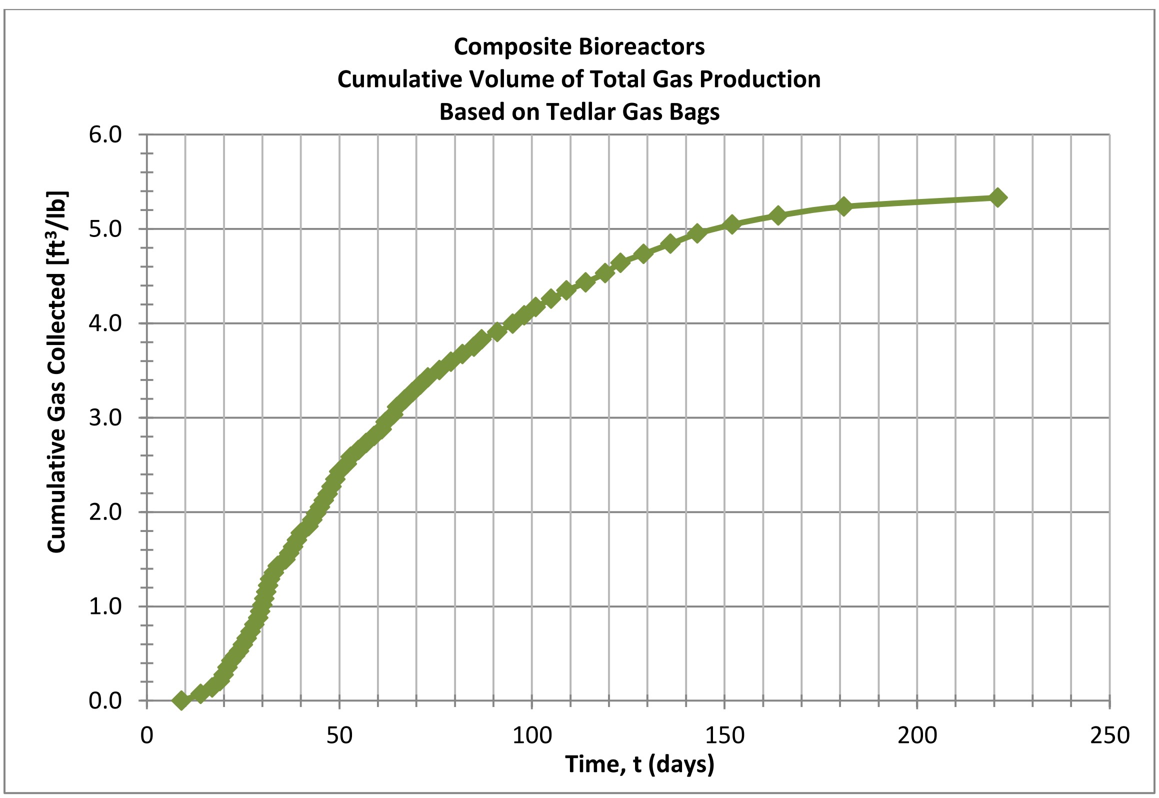

Figure 5.9 Cumulative Volume of Total Gas Produced From Composite Tedlar Bags

Table 5.4 Comparison of Decay Constant for Composite Bioreactor Set

Author	Decay Constant, k_n [$year^{-1}$]					Time Range [day]		
	Linear, m (slope)	Readily, k_r	Moderately, k_m	Slowly, k_s	Overall, k_c	t_1	t_2	t_3
Lifrieri (2010)	0.0112	0.0243	0.0099	0.0002	0.011	35	60	270
Shah (2015)	0.0478	0.0370	0.0140	0.0021	0.017	30	50	200

As indicated in Chapter 3, the author repeats that the decay constants, "k_n" are not directly comparable to those presented by Findikakis et. al (1979) and based on waste half-life, "λ_n". Those developed by Lifrieri are more closely relatable to the EPA LandGEM decay constant than the half-life constants suggested by Findikakis and Durmusoglu (2005). Lifrieri notes in his work that default values suggested by Findikakis et al. (1979) were used to formulate conclusions in lieu of the decay constants developed by his work since Findikakis' work was conducted on field-scale conditions. Likewise the half-life decay constants (λ_n) suggested by Durmusoglu (2005) are utilized by this author since the constants obtained by this work represent ideal conditions under a controlled environment and the represent a smaller sample size. The development of laboratory half-life decay constants and comparison to those suggested by Findikakis et. al and Durmusoglu are discussed further in Chapter 6.

5.2.2 Total Gas Data Collected from Readily Degradable Tedlar Bags

Data collected from the tedlar gas bags connected to the readily degradable bioreactor set indicated a peak 10-day volume of 2.043 cubic feet of total gas per pound waste occurring approximately 40 days into the experiment. Summation of the actual gas bag volumes for all bags used indicated approximately 8.877 cubic feet of total gas per pound of waste were collected over a 221 day period. Based on the observation, a best-fit exponential expression results in a descriptive constant, k_r, for the readily degradable bioreactor set of 0.045 year^{-1}.

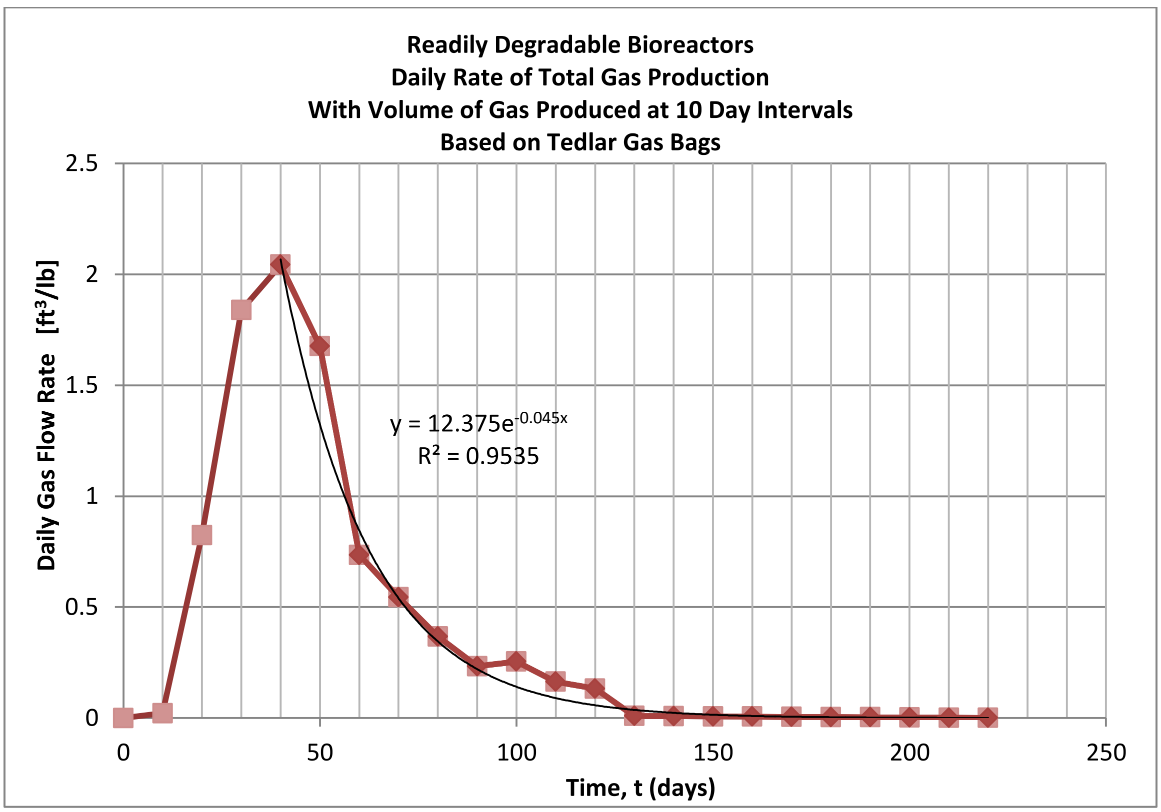

Figure 5.10 Daily Volume Of Total Gas Produced From Readily Degradable Tedlar Bags

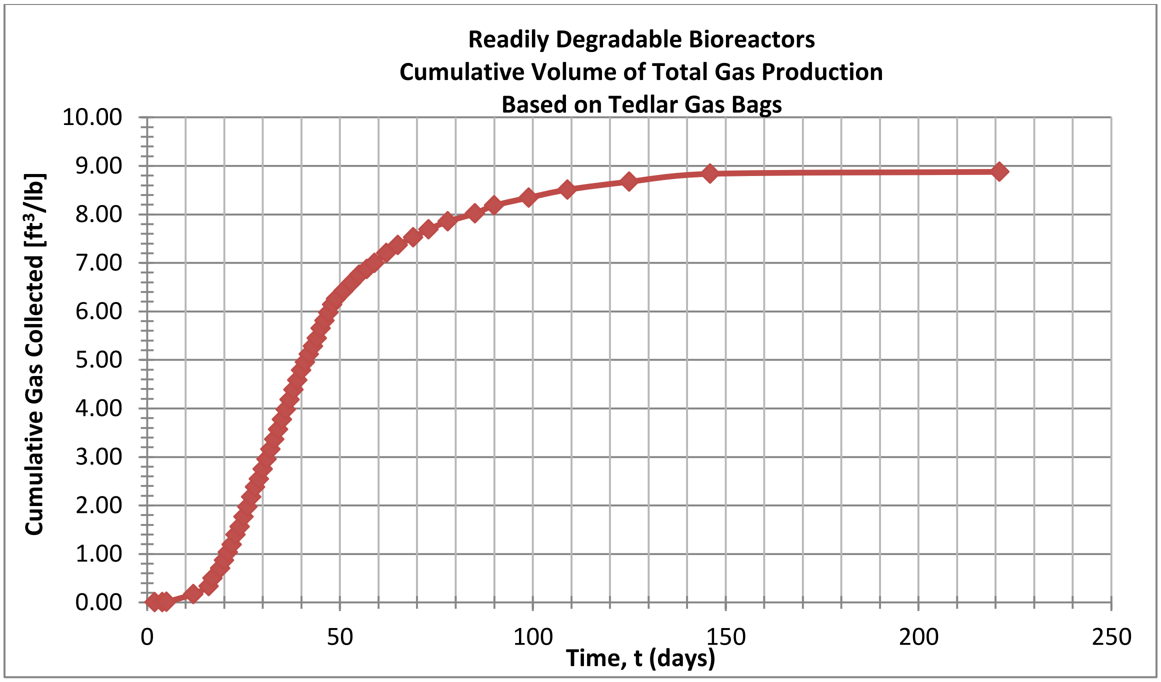

Figure 5.11 Cumulative Volume of Total Gas Produced from Readily Degradable Tedlar Bags

5.2.3 Methane Gas Data Collected from Moderately Degradable Tedlar Bags

Tedlar gas bag data collected from the moderately degradable bioreactor set indicated a peak 10-day volume of 0.539 cubic feet of total gas per pound waste occurring approximately 80 days into the experiment. Summation of the actual gas bag volumes for all bags used indicated approximately 5.796 cubic feet of total gas per pound of waste were collected over a 261 day period. As indicated earlier, gas collection for the moderately degradable bioreactor was maintained for a period longer than others since filling of secondary tedlar bags was observed, although the primary flow meter did not register flow. Gas collection was continued until no visible change in gas bag volume could be observed for a continuous 5 day period. Based on the observation, a best-fit exponential expression results in a descriptive constant, k_m, for the moderately degradable bioreactor set of 0.012 year^{-1}.

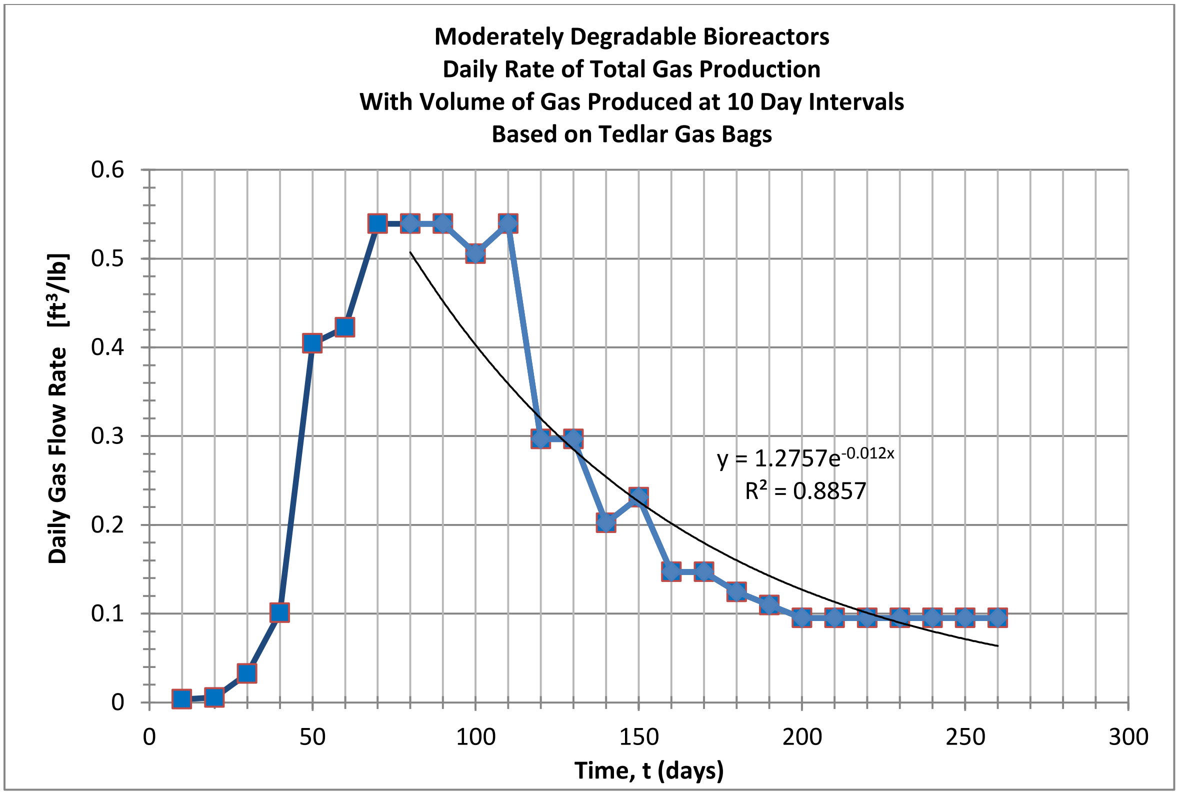

Figure 5.12 Daily Volume of Total Gas Produced from Moderately Biodegradable Tedlar Bags

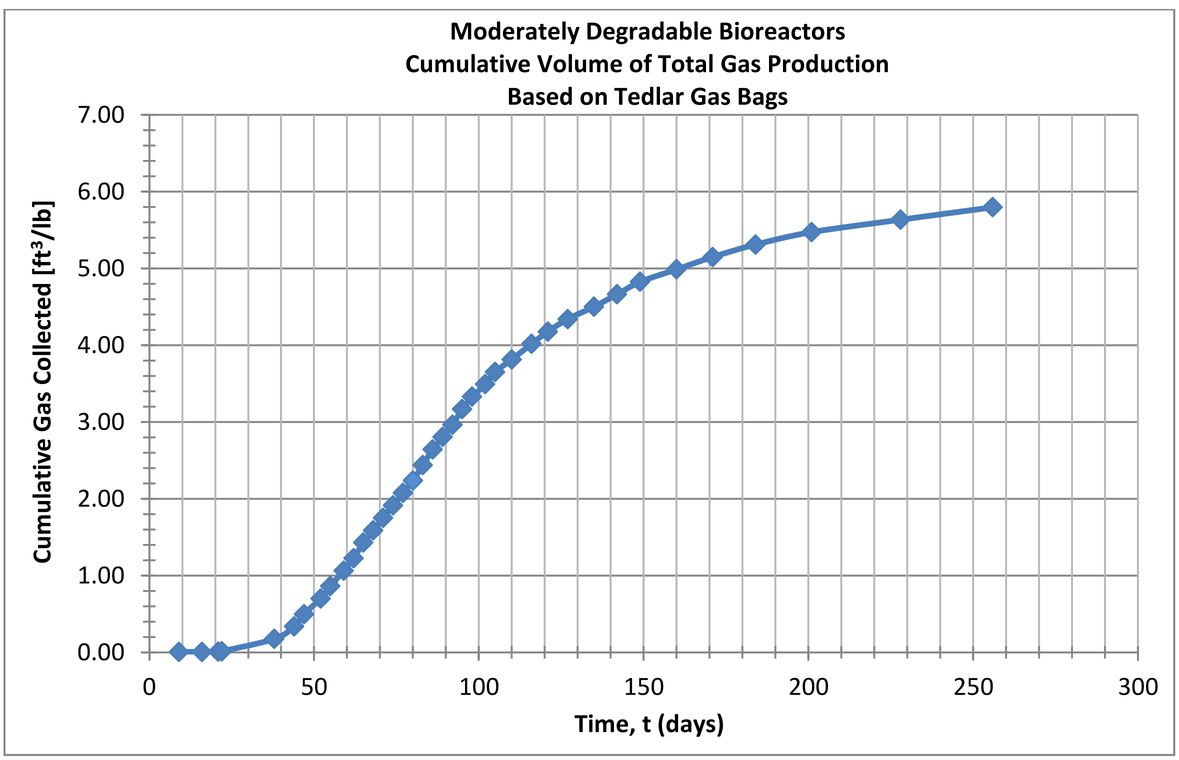

Figure 5.13 Cumulative Volume of Total Gas Produced from Moderately Degradable Tedlar Bags

5.2.3 Total Gas Data Collected from Slowly Degradable Tedlar Bags

As indicated previous, tedlar gas bags were utilized as the primary means for evaluating total gas flow rate and volume as the sensitivity of gas flow meters prohibited its use for the slowly degradable bioreactor set. The author observes that the data supports a peak rate of gas production occurring approximately 90 days into the experiment. After this time, gas production occurs at a nearly steady rate. The cumulative volume of gas approach is nearly linear, compared to other bioreactor sets which are characterized by an increasing form exponential decay curve. Therefore, the author suggests a descriptive constant, k_s, for the slowly degradable bioreactor set of 0.0021 $year^{-1}$as observed from the composite bioreactor set.

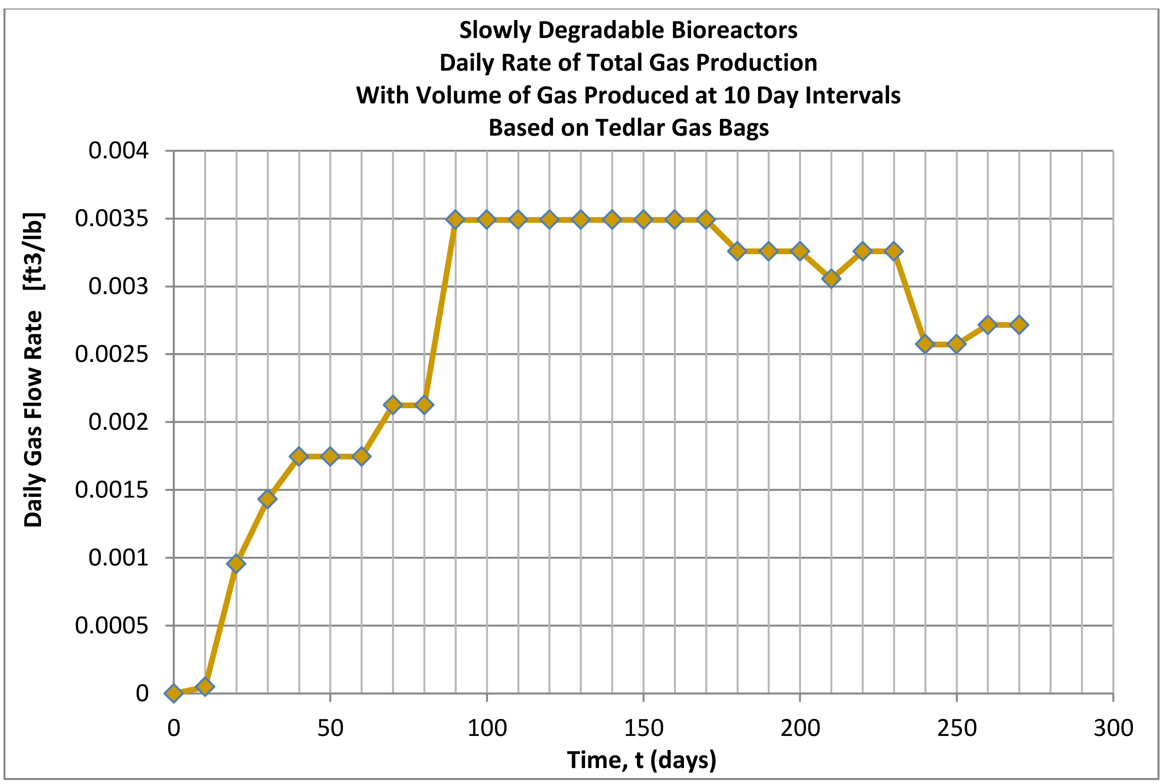

Figure 5.14 Daily Volume of Total Gas Produced from Slowly Degradable Tedlar Bags

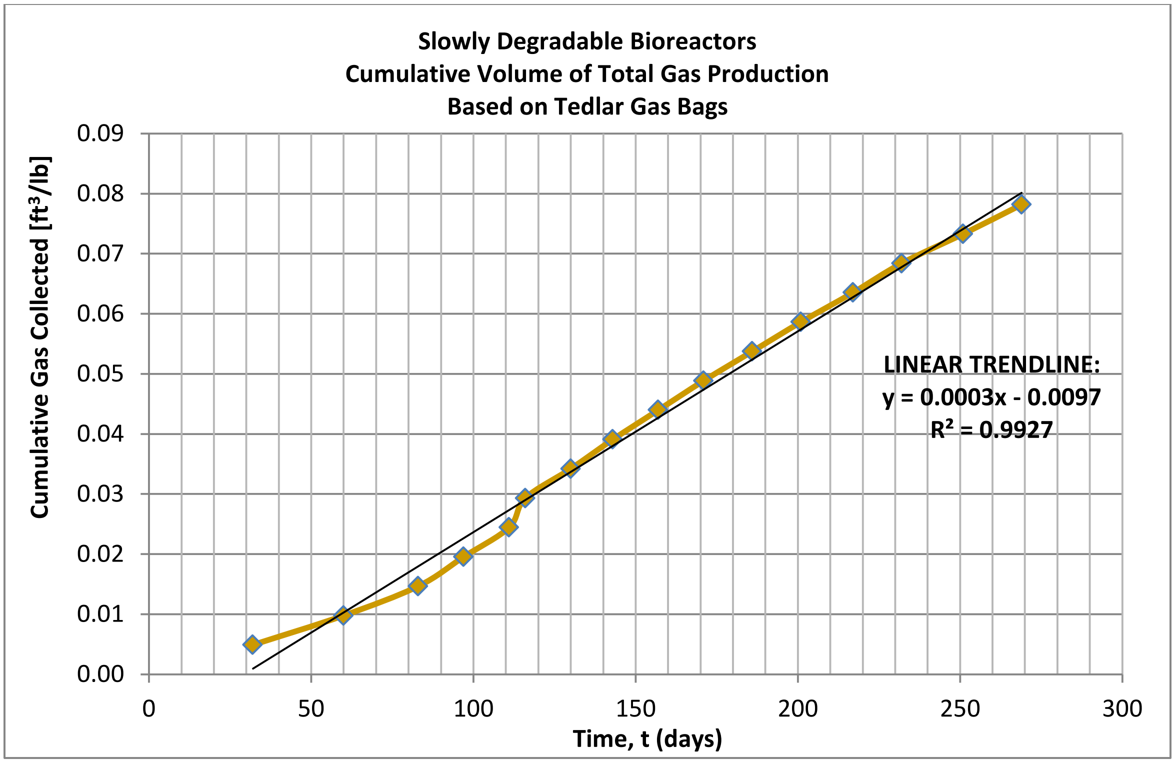

Figure 5.15 Cumulative Volume of Total Gas Produced from Slowly Degradable Tedlar Bags

Table 5.5 summarizes data collected from the tedlar gas bags for the composite, readily, moderately, and slowly degradable bioreactor sets. A comparison to the volume reported by flow meters is also presented in the table.

Table 5.5 Summary of Data Collected by Tedlar Gas Bags and Flow Meter

Reactor Set	Max 10-day Flow Rate [ft^3/lb]	Day Since Start for Max Reading	Cumulative Volume Total Gas [ft^3/lb]	Calculated Daily CH_4 Flow Rate [ft^3/lb]	Calculated Vol. of CH_4 Gas Collected [ft^3/lb]	Comparison to Volume Reported by Flow Meters [%]
Composite	1.373	30	5.332	0.076	2.933	+ 10.9%
Readily	2.043	40	8.877	0.112	4.882	+ 5.6%
Moderately	0.539	80	5.796	0.030	3.188	+ 11.5%
Slowly	0.003	90	0.078	0.0002	0.043	(n.a.)

The author suggests the additional volume collected by the gas bags in comparison to gas flow meters is likely due to the production and capture of trace landfill gases produced during early phases of decomposition.

5.3 Consolidation Test Results

Consolidation tests were performed in accordance with the procedure and schedule identified in Chapter 4 and Table 4.5, respectively. Load parameters for the samples to simulate self-weight and applied loads of landfills of variable heights were computed from resulting data. Compression parameters, including immediate compression, primary compression (C'_c), inorganic secondary compression (C'_α), and biodegradation compression (C'_β), were determined at the specific states of decomposition observed from testing.

Results from consolidation testing as strain versus time plots for all samples are graphically provided as Figure 5.16. Generally, the author observed elastic settlement occurred rapidly, within one to four minutes after load placement. This was followed by primary compression (C'_c) which occurred within 12 to 15 hours after load placement. Secondary and creep-driven compression indices C'_α and C'_β occurred within 30 days to 2 months following final load placement.

Table 5.6 is provided to summarize the results of the consolidation testing and resulting compression indices obtained from the work. Two samples were tested from each bioreactor to provide redundancy and were labeled based on bioreactor number and sample number. For example, consolidation tests 1 and 2 for bioreactor C-1 were labeled C-1-1 and C-1-2, respectively.

The author includes approximate percent biodegraded at the time the sample was removed and placed into the consolidation frame. The percent biodegraded is approximated by actual gas collection and theoretical gas potential and is provided to observe time variations of the parameters as decomposition progresses.

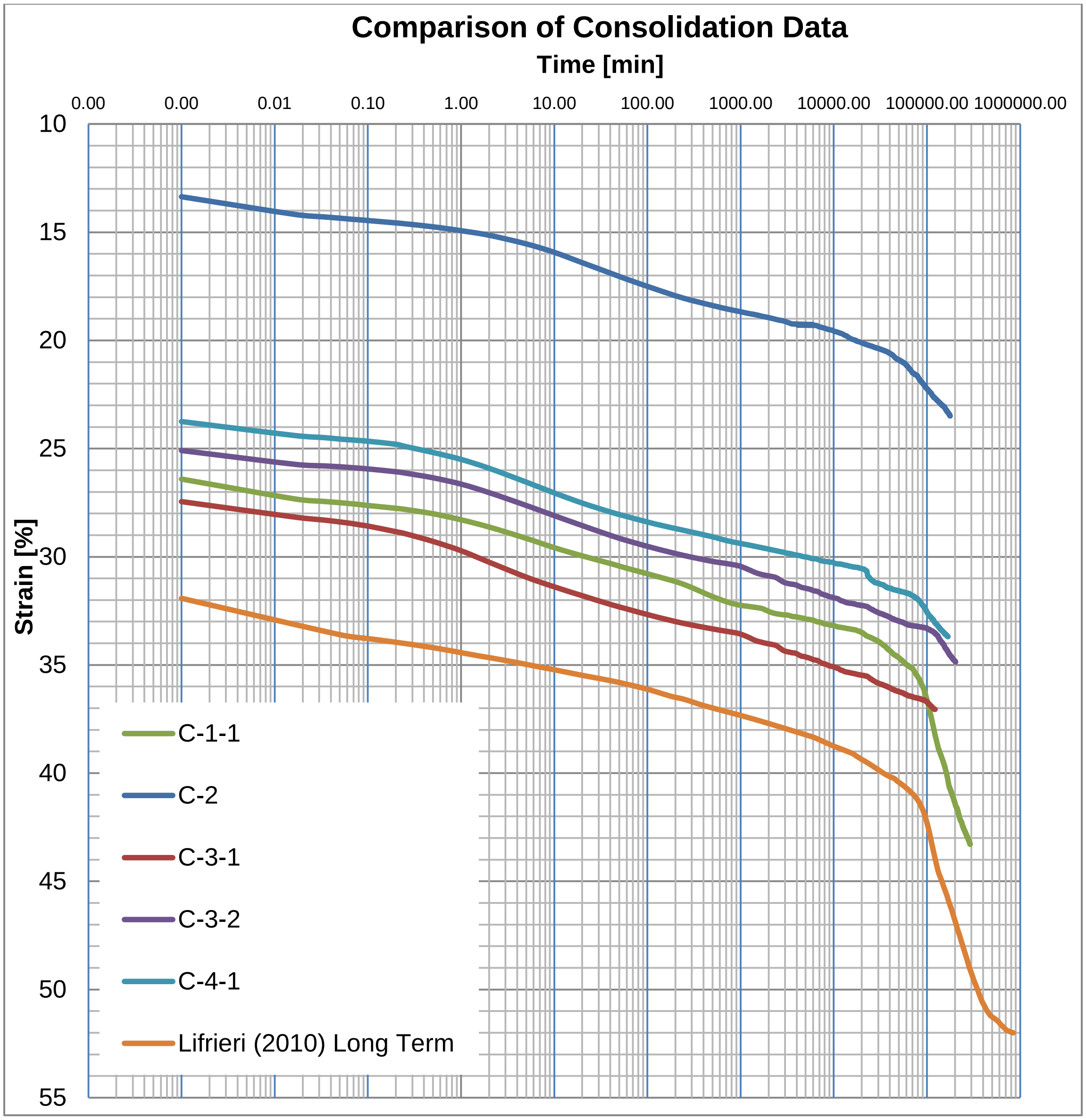

Figure 5.16 Consolidation Testing Results For All Samples at 4.40 tsf

Table 5.6 Compression Parameters Obtained from Consolidation Testing

Test	Approx % Biodegraded (from gas production)	C'_c	C'_α	C_β
C-1-2	29%	0.2341	0.0098	0.144
C-1-2	29%	0.2143	0.0094	0.035
C-2-1	37%	0.2313	0.0053	0.056
C-2-2	37%	0.1864	0.0048	0.067
C-3-1	53%	0.2103	0.0062	0.054
C-3-2	53%	0.1986	0.0067	0.053
C-4-1	62%	0.1948	0.0070	0.041
C-4-2	62%	0.2031	0.0068	0.062
C-5-1	67%	0.1996	0.0076	0.058
C-5-2	67%	0.2003	0.0081	0.051
C-Final-1	73%	0.2129	0.0053	0.036
C-Final-2	73%	0.2133	0.0056	0.042

Since the initial waste composition was identical to that used by Lifrieri (2010), the author suggests that the use of the long-term test data collected by Lifrieri to calculate $C_{\alpha\beta}$ and Secant$_\beta$ may be possible if a similarity exists between the two data sets. The index $C_{\alpha\beta}$, used to predict tertiary, non-biodegradation related settlement, and Secant$_\beta$ used to predict future tertiary settlement until the waste has stopped compressing, occur according to creep mechanics and therefore are not the focus of this work.

Figure 5.17 graphically depicts a comparison of the two data sets, which indicates a C'_α of 0.0098 and C'_β of 0.1440 as obtained by the author and a C'_α of 0.0090 and C'_β of 0.1470 as obtained by Lifrieri (2010). Likewise the time durations for the four of five compression phases occurring during the time range considered for comparison are observed to be analogous. Therefore, the author suggests that the two data sets are characteristically identical, and that C'_α and C'_β are comparable. Additional background regarding the phases of compression is presented in Chapter 2 and graphically in Figure 2.3.

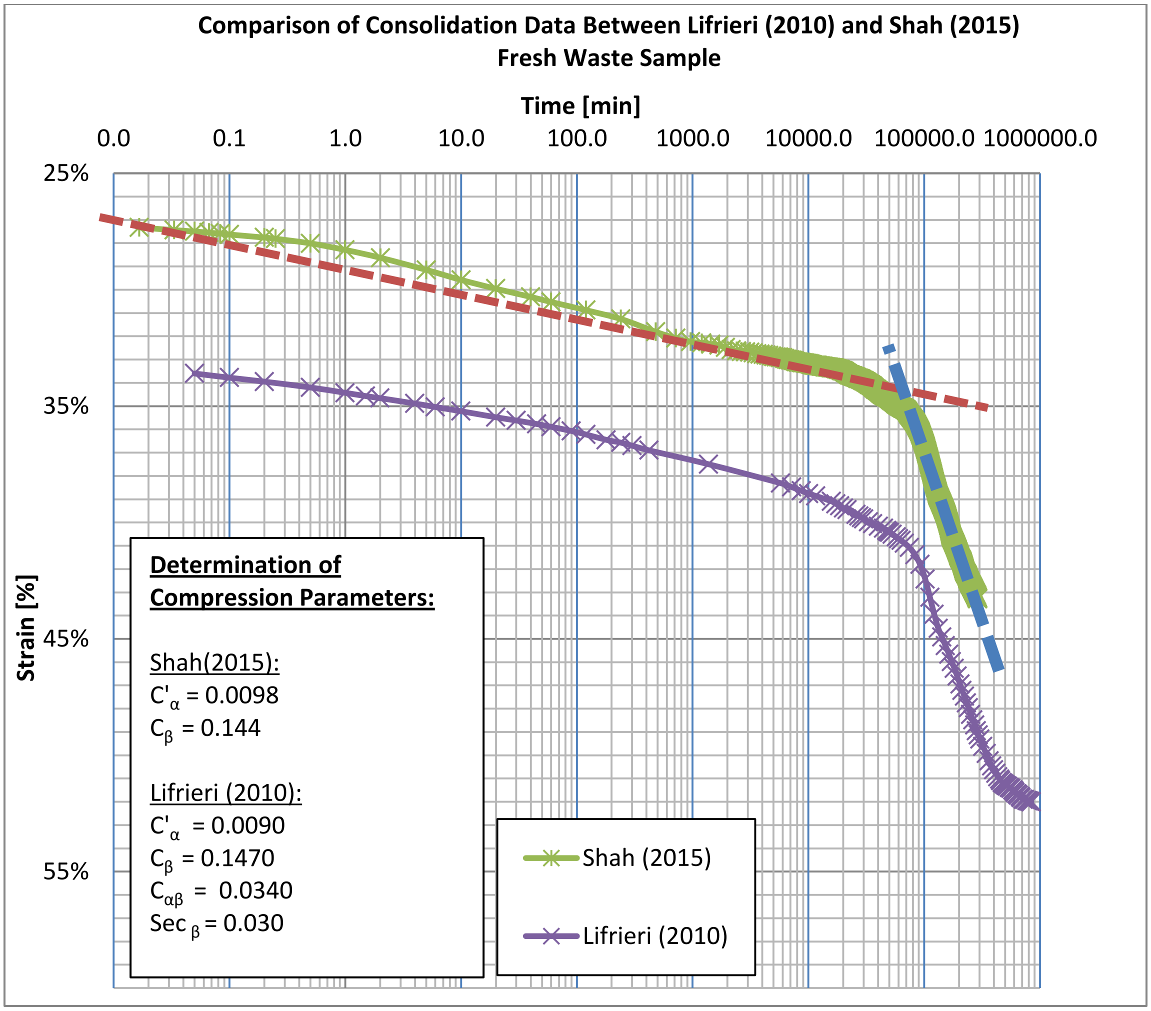

Figure 5.17 Comparison of Consolidation Data Between Lifrieri (2010) and Shah (2015) for Fresh Waste Sample

The author comments that an approximate 8 percent disparity exists between the data sets for strain of the sample at initial load placement; however, it is suggested that the method of compaction of the material as placed into the consolidation cell, thickness of lifts in the cell, geometry of waste particles, or presence of localized large, generally incompressible particles such as glass or plastic may affect elastic compression and result in the minor difference.

At the end of the experiment, the author tested two samples (C-Final-1 and C-Final-2) from a decommissioned composite bioreactor to analyze the compression indices representative of waste at the practical end of decomposition. Figure 5.18 presents strain versus time plots for both end of biodegradation samples tested. It is remarked that the distinctive increase in slope during the fourth, range of biodegradation compression (C'_{β}), phase indicative of biodegradation is absent. Instead, the compression appears to advance from inorganic secondary compression to tertiary compression. However this is anticipated as biodegradation is expected to be complete and biodegradation compression is therefore minimal compared to the other controlling mechanisms.

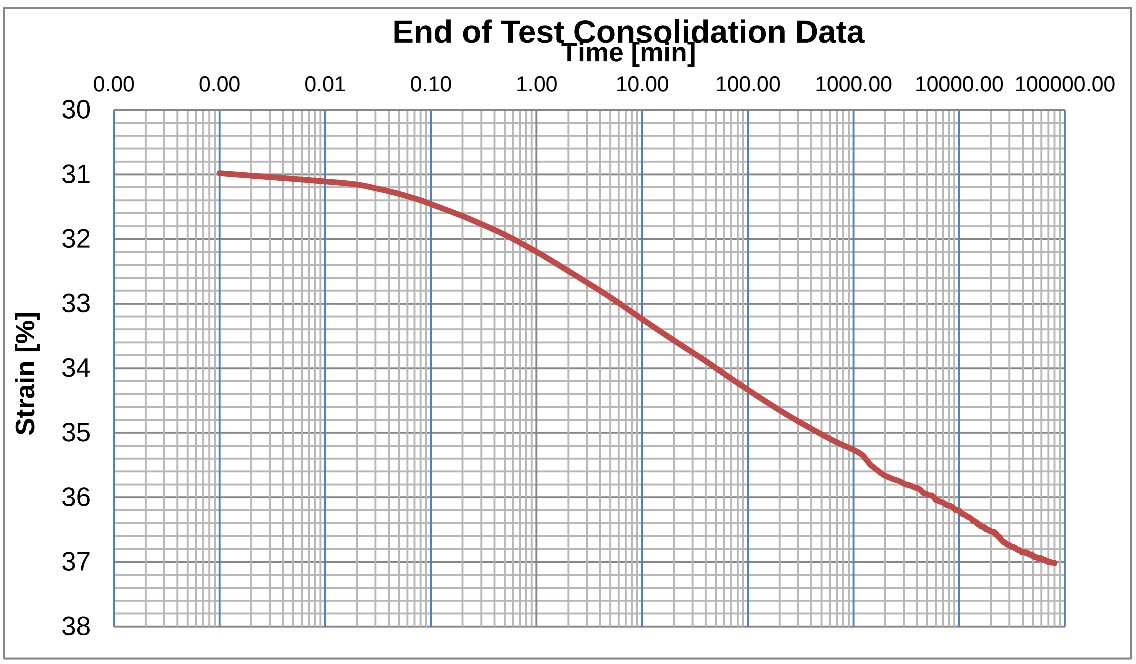

Figure 5.18 Strain Versus Time Plot for End of Decomposition Sample

Originally it was proposed to utilize compression characteristics as a function of (C+H)/L to determine the strain attributed to the biodegradation phenomenon. However, subsequent deviation from the use of (C+H)/L resulting from shortcomings of the test prompted the author to propose a strain relationship using measurement of biodegradable mass and volume changes instead. However, as tests were completed, available data was compared against that collected by Lifrieri (2010). This was used to validate this data for consistency, accuracy, and dependability of the method and data. It is noted that the work and model proposed herein solely aim to predict biodegradation-related strain. Mechanical strain due to imposed pressure other than self-weight are outside the scope of this work.

5.4 C+H/L Test Results

As discussed in Chapter 4, bioreactors decommissioned to test for compression testing were subsequently sampled and sent for (C+H)/L testing to determine the state of biodegradation of the waste. Samples were sent to Dr. Morton A. Barlaz at North Carolina State University for (C+H)/L testing. Complete data, as received by Dr. Barlaz, is provided under Appendix B.6 – (C+H)/L Test Record.

Table 5.7 and 5.8 summarize the results of the samples submitted for (C+H)/L during the course of work. The table indicates cellulose, hemicellulose, lignin and biodegradable solids as percent of the waste mass. Two tests were completed for each sample and an average presented of the test results. A Relative Percent Deviation (RPD), defined as the standard deviation divided by the average (reported in percent) is presented to quantify precision of the test. A low Relative Percent Deviation would indicate lower variability of the test data, while a higher percentage would indicate the data is more varied. Sample results obtained from this work were observed to have low Relative Percent Deviation.

Table 5.7 Summary of Cellulose + Hemicellulose over Lignin Tests

	% Cellulose				% Hemicellulose				% Lignin			
Sample	**Rep 1**	**Rep 2**	**Avg.**	**RPD [%]**	**Rep 1**	**Rep 2**	**Avg**	**RPD [%]**	**Rep 1**	**Rep 2**	**Avg.**	**RPD [%]**
C-Initial-1	44.96	51.54	48.25	9.6	9.15	10.14	9.65	7.3	4.70	4.42	4.56	4.3
C-Initial-2	43.42	42.72	43.07	1.1	9.88	8.89	9.39	7.5	4.77	5.04	4.91	3.9
R-Initial-1	47.22	53.06	50.14	8.2	5.23	5.87	5.55	8.2	6.02	5.51	5.77	6.3
R-Initial-2	55.02	53.67	54.35	1.8	4.45	4.51	4.48	0.9	5.27	5.42	5.35	2.0
M-Initial-1	40.90	39.76	40.33	2.0	10.2	10.75	10.47	3.8	3.87	4.13	4.00	4.6
M-Initial-2	51.51	47.67	49.59	5.5	11.7	10.58	11.17	7.5	4.37	4.46	4.42	1.4
C-1-1	10.41	8.37	9.39	15.4	4.90	3.72	4.31	19.4	21.94	21.75	21.85	0.6
C-1-2	14.43	9.43	11.93	29.6	6.34	4.68	5.51	21.3	22.30	21.63	21.97	2.2
C-2-1	19.55	18.72	19.14	3.1	5.99	5.78	5.89	2.5	25.81	25.19	25.50	1.7
C-2-2	15.76	14.14	14.95	7.7	6.62	5.68	6.15	10.8	26.80	27.08	26.94	0.7
C-3-1	11.48	10.79	11.14	4.4	4.73	4.13	4.43	9.6	24.67	23.67	24.17	2.9
C-3-2	8.61	9.11	8.86	4.0	3.53	3.95	3.74	7.9	20.85	22.01	21.43	3.8
C-4-1	7.08	7.30	7.19	2.2	2.43	1.82	2.13	20.3	20.72	22.11	21.42	4.6
C-4-2	7.36	6.63	7.00	7.4	2.42	1.78	2.10	21.5	20.92	20.69	20.81	0.8
C-4-3	5.43	5.20	5.32	3.1	2.31	2.78	2.55	13.1	31.84	30.50	31.17	3.0
C-4-4	6.45	4.60	5.53	23.7	2.78	1.81	2.30	29.9	33.62	40.15	36.89	12.5
C-Initial retest-1	51.26	39.45	45.36	18.4	7.98	6.38	7.18	15.8	5.09	5.37	5.23	3.8
C-Initial retest-2	44.18	44.66	44.42	0.8	6.40	7.08	6.74	7.1	13.89	14.27	14.08	1.9

Table 5.8 Summary of Cellulose + Hemicellulose over Lignin Tests (continued)

	% Lipophillic Extractives				% Organic Solids				C+H / L	C+H+ / LVS
Sample	**Rep 1**	**Rep 2**	**Avg.**	**RPD [%]**	**Rep 1**	**Rep 2**	**Avg.**	**RPD +- 25% [%]**	**From avg**	**From avg (%)**
C-Initial-1	-2.43	-2.14	-2.29	-9.0	78.5	79.6	79.05	1.0	12.70	0.76
C-Initial-2	-3.28	-3.33	-3.31	-1.1	80.4	80.7	80.55	0.3	10.69	0.67
R-Initial-1	-1.99	-2.08	-2.04	-3.1	97.6	97.5	97.55	0.1	9.66	0.61
R-Initial-2	-2.01	-2.10	-2.06	-3.1	97.3	97.3	97.30	0.0	11.01	0.64
M-Initial-1	-3.65	-3.51	-3.58	-2.8	78.0	78.0	78.00	0.0	12.70	0.66
M-Initial-2	-3.53	-3.53	-3.53	0.0	77.4	77.6	77.50	0.2	13.76	0.80
C-1-1	-0.47	-0.50	-0.49	-4.4	52.5	53.1	52.80	0.8	0.63	0.66
C-1-2	-0.35	-0.12	-0.24	-69.2	52.0	52.0	52.00	0.0	0.79	0.75
C-2-1	-1.30	-1.24	-1.27	-3.3	66.4	65.8	66.10	0.6	0.98	0.75
C-2-2	-1.49	-1.11	-1.30	-20.7	56.1	58.1	57.10	2.5	0.78	0.82
C-3-1	1.28	1.18	1.23	5.7	50.8	51.5	51.15	1.0	0.64	0.80
C-3-2	1.48	1.61	1.55	5.9	48.4	47.7	48.05	1.0	0.59	0.74
C-4-1	1.35	1.40	1.38	2.6	47.4	48.2	47.80	1.2	0.43	0.67
C-4-2	0.94	0.94	0.94	0.0	45.1	43.6	44.35	2.4	0.44	0.70
C-4-3	1.17	0.97	1.07	13.2	39.4	38.8	39.10	1.1	0.25	1.03
C-4-4	0.86	0.85	0.86	0.8	41.4	43.8	42.60	4.0	0.21	1.07
C-Initial retest-1	4.90	4.65	4.78	3.7	72.5	74.1	73.30	1.5%	10.04	0.85
C-Initial retest-2	3.95	4.02	3.99	1.2	76.1	77.5	76.80	1.3%	3.63	0.90

Evaluation of the above data indicates a drastic decrease in (C+H)/L occurring during early stages of decomposition. These stages are designated between initial sampling of fresh waste (C-Initial-1 and C-Initial-2) and the first sample for testing (C-1-1 and C-1-2). The rate of decrease, which is characterized similar to an exponential decay, approaches an asymptotic value as time increases and when decomposition moves forward at slow rate. This is comparable to work completed by Lifrieri (2010) who suggests that biodegradation is essentially complete once the (C+H)/L ratio becomes consistent, and further biodegradation settlements occur at a minimum. While the rate of decay is much greater than that observed by Lifrieri, and the stabilization of (C+H)/L occurring earlier during this work, the author suggests this is likely due to the samples being treated similar to a bioreactor landfill to promote degradation. Similarly, the removal of plastics and other synthetics further appear to amplify the decrease in (C+H)/L which appears drastic from 11.14 to 0.71.

Additional (C+H)/L tests were not completed by this author after 122 days into the work as the change between test results appeared insignificant, supporting that further testing would not yield meaningful results. It is acknowledged by the author as well as others (Barlaz 2014, De la Cruz 2014, De la Cruz 2012, Kim 2004) that (C+H)/L test results are not a reliable indicator during decomposition to quantity the relative state of decomposition during intermediate stages of degradation.

It should be noted that the original intended development of the (C+H)/L test was for agriculture purposes. The test was intended for use in the food and wood pulp (paper) industries to measure loss of carbohydrates during long-term storage and transport processes. The test standard governing the method, ASTM E-1758 – "Standard Test

Method for Determination of Carbohydrates in Biomass by High Performance Liquid Chromatography", likewise indicates the primary use for processing and storage of agricultural produce and residues. By nature, inert and synthetic materials such as plastics were not expected in the originally used form of the test. The use of (C+H)/L to measure waste degradation has been suggested by select authors since the late 1980s (Tchobanglous, 1993), and has seen more widespread use in the mid-1990s. However, recent understandings are revealing limitations in the reliability and use of the test to determine state of biodegradation of mixed MSW.

The author observes that a (C+H)/L ratio of 3.96 obtained by Lifrieri (2010) for the initial sample representing fresh waste is much lower than the average of 11.14 for fresh waste representing the composite bioreactor obtained through this work. While the values obtained by Lifrieri are within the typically reported range of 1.6 and 6.35 (Barlaz 2006) for fresh waste, it is expected that higher values will be obtained from this work as a result of the removal of plastics and synthetics prior to testing. It is shown by the author that these synthetics add an artificial source of lignin, as examined below.

As discussed in Chapter 4, prior to submission for testing, samples were processed by removing plastics and synthetics from the sample. These constituents were removed as it was shown plastic and synthetic constituents do not dissolve in a 72 percent w/w solution of sulfuric acid (De la Cruz 2014, Barlaz 2014). Consequently, these constituents would act as recalcitrant fossil carbon, and act as synthetic lignin which would artificially increase the lignin content of tested sample as a result (De la Cruz, Chaton, and Barlaz 2012). Work conducted by Kim (2004), in which samples were also analyzed by a laboratory independent of Dr. Barlaz, supports this claim.

To confirm this hypothesis, the author batched and tested a fresh sample of waste identical to the initial samples tested at inception of the experiment to understand the effect of removing plastics and synthetics and the resulting impact on the (C+H)/L ratio. In one sample, “C-Initial restest-1”, the waste was processed and plastics and synthetic constituents were manually removed from the sample. A second sample, “C-Initial retest-2” was unprocessed and unaltered to be used as a comparison.

From the reported results, the percent cellulose of the sample with plastics removed is 45.36 percent and unprocessed is 44.42 percent. The percent hemicellulose of the sample with plastics removed is 7.18 percent and unprocessed is 6.74 percent. Therefore, it is observed that reported cellulose and hemicellulose between the samples are near identical. Lignin content of the sample with plastics and synthetics removed was 5.23 percent, whereas the lignin content of the unprocessed sample was reported as 14.08 percent. The resulting (C+H)/L of the samples were 10.04 and 3.63, respectively.

In this instance, by maintaining the numerator of (C+H) as 51%, it is the author’s opinion that inclusion of plastic and other synthetics would act as artificial lignin and report reduced ratios of (C+H)/L within the typically reported range of 1.6 and 6.35 (Barlaz 2006) for fresh waste and as indicated above.

Based on discussion with Dr. Morton Barlaz (2014), it is understood the (C+H)/L of fresh MSW tested by himself in 2006 has been reported to be in this range of 1.6 to 6.35, with five of eight values above 3.2. It is noted by Dr. Barlaz that his 2006 work indicated that the three lowest values in this dataset (1.64, 1.68, and 2.15) are suspect as they contain between 23 to 28 percent lignin, respectively. Dr. Barlaz suggest that, as newsprint is reported to contain about 23 percent lignin (Barlaz 2006), and various types of lumber contain 23 to 33 percent lignin (Wang et al. 2011), the presence of 23 to 28 percent lignin in MSW is unreasonable. Since mixed MSW contains 15 to 20 percent vegetative waste, it is unreasonable the entire sample would have the lignin content close to fibrous, vegetative waste. One would expect lignin content to be much lower, in the range of 3 to 7 percent, for a mixed MSW. Therefore, this discrepancy for elevated lignin is likely attributable to interference by synthetic lignin within mixed MSW.

In addition to the above, the author comments that there are two types of carbon: 1) biogenic carbon, which results from photosynthesis and natural processes such as simple sugars and vegetation and, 2) fossil carbon, which is derived from fuel-stored carbon such as plastics and by-products of oil refinement. De la Cruz, Chaton, and Barlaz (2012) further describe the conflict of lignin in their discussion of the carbon potential of waste, expressed as percent biogenic carbon (which is degradable) and carbon storage (which remains in a landfill).

This carbon potential stored in a landfill can further be distinguished by its components, which include fossil-carbon that comes from petroleum-derived products such as plastics and synthetic textiles, and biogenic carbon that originates from food waste, yard waste, paper, and wood. The carbon associated with fossil-carbon was originally stored (within a buried petroleum reservoir) prior to burial in a landfill, so it is recommended by De la Cruz, Chaton, and Barlaz that only biogenic carbon should be evaluated to determine contribution to carbon storage (as lignin). It is shown by the above authors that not all of the cellulose and hemicellulose in MSW is degradable, and these remnant compounds may also contribute to carbon storage. Therefore biogenic carbon which does not degrade is considered to be stored, in addition to the carbon storage which can be attributable to fossil-carbon (artificial lignin).

An evaluation of 49 samples tested for percent cellulose, hemicellulose, lignin, biogenic carbon, and biochemical methane potential (BMP) for waste samples of varying age was conducted by De la Cruz (2014). From his work, De la Cruz indicated that, as the waste aged, a plot of the ratio of cellulose and hemicellulose versus lignin indicated a decreasing trend. This non-linear trend was similar to the trend observed by this work, as well as Lifrieri (2010) and Barlaz (2006). However, a trend of the biogenic carbon versus the ratio of cellulose and hemicellulose versus lignin indicated an opposite trend in comparison, such that lower ratios of cellulose and hemicellulose versus lignin indicated higher biogenic carbon. As indicated previously, even the carbon storage (fossil carbon) will have some percentage of biodegradable carbon within it. Therefore, to yield useful comparison, the proportion of biogenic carbon within the fossil carbon needs to be evaluated. This may be difficult to evaluate, as during acid hydrolysis testing, not all but some portion of biogenic carbon within the fossil carbon will react.

De la Cruz (2014) explained that as the cellulose and hemicellulose versus lignin ratio decreases, the contribution of the remaining fraction of biogenic carbon is shielded by interference by fossil carbons (such as plastics). In other terms, as the waste sample degrades and at lower (C+H)/L, one would expect lower availability of biogenic carbon. Hence, this trend does not represent what is occurring and is contrary to what is anticipated. Barlaz (2006) subsequently indicates that (C+H)/L has been used for several decades to characterize the state of decomposition, and the quantification of cellulose and hemicellulose is based on measurement of sugars after acid hydrolysis is not subject to interference from extraneous materials in waste. However, lignin concentration, defined as Klason lignin and as the organic matter which does not dissolve during acid hydrolysis, is volatile at 550 °C and is subject to significant interference (Petterson and Schwandt, 1991) by recalcitrant synthetic lignin.

It was believed by this author and Lifrieri (2013) that this interference may be resolved by manually removing the rubber, plastic and synthetic textiles shown in the waste characterization study for the waste region of interest, determining the remaining constituents percentages by normalizing the overall waste, and preparing lab test samples without the suspect constituents for testing.

However, De la Cruz, Chaton, and Barlaz (2012) observed two limitations exist to the lignin analytical method that contribute to the variability in data: first, the inclusion of synthetics such as plastics, textiles, and rubber and resulting measurement of these as Klason (artificial) lignin as discussed previously, and second, that not all lignins are equal in their ability to limit the bioavailability of cellulose and hemicellulose. The authors indicate that, although the fossil carbons are generally inaccessible, some portion may act as biogenic carbon. This percentage is based on the source, manufacturing process, and other factors and is not identical for all synthetics. Therefore, removing plastics and synthetics completely from a sample will still remove a portion of the bioavailable carbon. Finally, it is understood that there are even variations between the lignin found in biogenic sources, such as those in wood and grass soft tissue relative to woody tissue (Eleazer et al., 1997, Lin and Dence, 1992, Sarakanen and Ludwig, 1971).

To confirm this hypothesis, the author tested two sets of samples at the end of the experiment to understand the effect of removing plastics and synthetics and the resulting effect on the (C+H)/L ratio. One sample set, consisting of samples “C-4-1” and “C-4-2”, was processed to remove plastics and synthetics prior to testing, while the second sample set, consisting of samples “C-4-3” and “C-4-4” were unprocessed and were sent for comparison to the traditional method of sampling and testing used by Lifrieri (2010) and others.

From the reported results, it is observed that cellulose and hemi-cellulose of the samples of the first set were approximately an average of 7.1 percent cellulose and 2.2 percent hemicellulose. Cellulose and hemi-cellulose of the unprocessed sample set were approximately 5.4 percent and 2.3, respectively. Lignin content of the sample with plastics and synthetics removed was 21.1 percent, whereas the lignin content of the unprocessed sample was reported as 34.0 percent. The average resulting (C+H)/L of the sample sets were 0.44 and 0.23, respectively.

It is observed that, although the hemicellulose content remains nearly similar for both sample sets, the cellulose content is lower in the unprocessed sample which may be attributed to the partial interference of lignin to accurately determine cellulose content. This interference becomes more aggressive during the initial stages of decomposition, during which time the proportion of cellulose and hemicellulose drop drastically (De la Cruz, 2014). Therefore, intermediate values of (C+H)/L are not reliable indicators of waste undergoing decomposition. The values may, however, be valid for fresh and end of decomposition determination of waste.

The author indicates that the work completed by Lifrieri suggest that (C+H)/L values stabilize 188 days into the work, which would indicate biodegradation is essentially complete; however, an additional 15 percent of total gas is collected over the next 120 day period. Likewise the data collected through this work indicate stabilization of (C+H)/L values approximately 122 days into the work; however gas production continues for approximately 100 more days. Therefore, the author believes that the (C+H)/L ratio provides mixed correlation to determine projected end of biodegradation.

The author notes that, during (C+H)/L testing, each sample was tested for percent organic solids measured by loss on ignition at 550 °C. The tests were conducted in accordance with the test procedures indicated by ASTM D7348 - “Standard Test Methods for Loss on Ignition (LOI) of Solid Combustion Residues”. It is observed by the test data supplied in Table 5.8 that the initial percent organic solids for the fresh waste sample (titled “C-Initial-1” and “C-Initial-2”) are approximately 80 percent. This is very close to the degradable fraction of the waste composition tested herein, which contained 81 percent biodegradable material. The work completed by Lifrieri (2010) with similar waste composition likewise indicated a similar average of 78 percent organic solids from fresh waste sample testing. Samples taken at the end of the experiment (titled “C-4-1” through “C-4-4”) indicate an average remaining percent organic solids of approximately 43 percent. Work conducted by Lifrieri (2010) indicated a similar average end percent organic solids of 4 percent. Therefore, a loss of approximately 37 percent of % organic solids had occurred throughout the experiment. The author has provided a comparative calculation in Table 5.9 to determine strain based on percent organic solids during (C+H)/L testing.

Table 5.9 Calculation of Percent Strain of Laboratory Bioreactors by Percent Organic Solids from (C+H)/L Testing

Step 1:	Assume original volume: $V_o = 1\ ft^3$
Step 2:	$V_{organic} = 80\% = 0.8\ ft^3$
Step 3:	$V_{inert} = 20\% = 0.2\ ft^3$ Tests indicate percent biodegradable content starts at 80% when fresh, to 44% at end of work
Step 4:	Therefore at end, $V_{organic@end} = 0.44\ V_1$ Where V_1 is the total volume at end
Step 5:	Assume final volume: $V_f = V_1$ Therefore, $0.44V_1 + 0.2 = V_1$ Since V_{inert} remains same, $0.2\ ft^{3,}$ $V_1 = 0.35\ ft^3$
Step 6:	Percent strain is $(V_1\text{-}V_o)/V_o =$ $(0.35\ ft^3\text{-}1)/1\ ft^3 = 65\%$

At the end of the experiment, bioreactors were decommissioned to measure the actual mass remaining, which indicated 29 percent of total mass remaining. This would indicate a strain of 71 percent, which is in close agreement to the calculated percent strain of 65 percent due to loss of percent organic solids.

Therefore, from the work conducted herein and by De la Cruz (2014) and De la Cruz, Chaton, and Barlaz (2012), it is suggested that (C+H)/L alone is not a useful indicator of decomposition in mixed MSW as the lignin measurement is not reliable. Therefore, although (C+H)/L sample testing was conducted by this author, is it not used as an indicator of relative biodegradation state of the waste as recommended by others. Therefore, in lieu of the (C+H)/L data, the author has proposed a correlation with loss of mass to determine state of biodegradation of the waste. This concept will be fully defined and discussed in Chapter 6. The author has provided additional discussion on the use and repeatability of using loss on ignition to determine percent organic solids in Section 5.7.

5.5 End of Test Bioreactor Measurements

Following completion of the experiment, remaining operational bioreactors were decommissioned after performing a series of measurements. The intent of the measurements was to understand the loss of biodegradable mass attributable to decomposition, changes in volume, compute percent biodegradation of the sample based on weight, observe any change in density of the waste sample, and verify moisture content of the bioreactor. Percent biodegradation ("%B") can be calculated by mass, or by volume, as further discussed in Chapter 7.

Generally, the decommissioning process consisted of saw-cutting the top of the bioreactor jar to expose the waste. The height of the sample was measured using a ruler with one-tenth inch markings to determine final density. Subsequently, the waste was removed from each bioreactor and placed into individual pans for measuring wet weight. The samples were oven-dried at low heat at 110°F to avoid burn-off of organic fractions, and the dry weight of the waste and moisture content of the sample were determined. Using bioreactor commissioning records at the start of the experiment, the original weights of biodegradable and non-biodegradable constituents were known and thereby allowing for a computation of the remaining weight of biodegradable fraction and percent biodegraded at the end of the experiment.

Table 5.10 summarizes average measurements of all bioreactors within a bioreactor set. Table 5.11 presents the change in waste sample density as result of biodegradation and self-weight compression. Table 5.12 indicates calculated percent biodegradation based on mass loss and measurements.

Table 5.10 Average of Measurements Collected During Decommissioning of Reactors

Reactor Set	Pan Weight [g]	Pan + Wet Sample Weight [g]	Wet Sample Weight [g]	Pan + Dry Sample Weight [g]	Dry Sample Weight [g]	W_{water} [g]	End Moisture Content [%]	Final Height of Sample [in]
Composite	102.50	706.92	604.43	513.77	411.28	193.15	47%	1.4
Readily	99.10	236.04	136.94	192.00	92.90	44.04	47%	0.3
Moderately	102.07	561.33	459.26	415.32	313.25	146.01	47%	1.0
Slowly	103.00	1997.03	1894.03	1377.47	1274.46	619.57	49%	4.4

Table 5.11 Determination of Change in Density During Decommissioning of Reactors

Reactor Set	Total End Wet Sample Weight [lb]	Total End Dry Sample Weight [lb]	*Glass [lb]*	*Soil [lb]*	*Original Wet Weight [lb]*	*Original Density [lb/ft^3]*	Final Density [lb/ft^3]	Change in Density [% of original]
Composite	1.33	0.91	0.24	0.17	4.60	40.73	37.07	91%
Readily	0.30	0.20	0.00	0.00	5.18	45.87	38.37	83%
Moderately	1.01	0.69	0.00	0.00	5.23	46.35	42.39	91%
Slowly	4.18	2.81	0.00	0.82	4.42	39.18	38.17	97%

Table 5.12 Determination of Percent Biodegraded During Reactor Decommissioning

Reactor Set	Original Volume (as dry) [ft^3]	Final Volume (as dry) [ft^3]	Total End Biodegradable Weight Remaining [lb]	Biodegradable Weight Lost [lb]	Original Weight of Degradable Constituents [lb]	Overall Average % Biodegraded
Composite	0.11325	0.03599	0.50	1.19	1.69	71%
Readily	0.11325	0.00797	0.20	1.90	2.10	90%
Moderately	0.11325	0.02391	0.69	1.41	2.10	67%
Slowly	0.11325	0.10948	1.99	0.11	2.10	5%

Appendix B.7 – End of Test Bioreactor Decommissioning Records tabulates all data recorded and evaluated during the decommissioning process. The author notes that italicized column headings indicate data which was obtained from commissioning records during the start of the experiment.

It can be observed that final density of the waste decreased slightly for each bioreactor set; however this is anticipated as the waste in the bioreactors are solely undergoing densification due to self-weight of material and mass reduction as a result of decomposition. This observation follows Durmusoglu et al. (2006), who performed an evaluation of total stress and bulk density spatial profiles for a deformable landfill at select time intervals and observed 10 to 15 percent densification as a result of self-weight of waste. The abovementioned authors observed that initial bulk density is decreased in the first 10 years of placement; however, in later years, bulk density increases due to landfill settlement caused by additional total stress from subsequent lifts and added load. Therefore, though the organic fraction of the waste undergoes mass reduction due to degradation and volume reduction resulting from deformation of the solid matrix, the author and those cited assume density to remain constant throughout the process.

Moreover, the author understands that in traditional soil mechanics, the solids comprising the soil are of inert materials. Therefore, any volume change corresponds to an increase in density as the weight of solids remains constant. However, in the case of waste, the materials consist of degradable solids; therefore, a reduction in the weight of solids occurs along with a reduction in the total volume as degradation proceeds. If the rate of loss of weight is greater than the rate of loss of volume, than the density would be seen to decrease.

5.6 Determination of End of Test

Several indicators were used to substantiate a determination to end the physical work conducted herein. At the time of the end of test, the author observed no further flow readings were being collected by the gas flow meter. Similarly, it was visually observed that minimal additional volume was being collected by secondary tedlar gas flow bags connected to the flow meters. These bags, which were used to measure and capture total gas flow, supported the diminishing rate of gas production.

In Chapter 6, the author presents and discusses a gas generation model to determine maximum field-observable gas generation using a natural logarithmic regression. Based on this method, the amount of methane gas which may be collected feasibly is 2.602 cubic feet per pound waste. Based on the 2.55 cubic feet of methane gas per pound waste collected as measured by the methane flow meter, approximately 98 percent of gas on a calculated total actual collectable methane gas basis was collected based on this model. For this measured value of methane gas, the total gas collected is approximately 4.63 cubic feet for a landfill gas with 55 percent methane proportion.

The author notes that the value of total gas recovered appears typical, as work conducted by Lifrieri (2010) on similar waste composition resulted in a total gas collection of 4.237 cubic feet per pound waste after 430 days of collection. Based on Lifrieri's work, the collected gas amounted to approximately 69 percent of the total calculated theoretical gas potential of 6.18 cubic feet per pound waste, or 88 percent of captureable total gas based on the maximum field-observable gas generation developed by the author.

The author suggests that, although generation of the remaining proportion of gas may occur for an extended period of time, it may be incapable of being measured. This limitation is attributable to the sensitivity of equipment and collection methods used.

Additionally, as indicated in Chapter 4, a landfill gas meter was connected to the secondary gas collection bags periodically to understand the composition of the gas generated. The percentage of CH_4, CO_2, and O_2 was recorded, with gas composition records provided under Appendix B.4 – Gas Composition Records. Toward the end of the experiment, the gas meter was attached individually to each of the four tedlar bags connected to bioreactor sets to ascertain which phase of biodegradation the bioreactor set was in by reviewing the proportion of percent methane, carbon dioxide, and trace landfill gases. Further discussion on expected proportions of gas generation was previously presented in Chapter 3.

From the characterization, it is the author's opinion that the proportions of methane and carbon dioxide were decreasing from an approximate 55-45 percent split. This decrease indicates the majority of readily available biodegradable organic material has been converted to individually during the previous methane fermentation phase and at the time the experiment was terminated. The data additionally supports that the biodegradation process was in its final phase during decommissioning of the test. This generally follows the trend suggested by Tchobanglous (1993), USEPA (2003), and ATSDR (2008).

Furthermore, the author discussed the phases of waste decomposition in Chapter 2, and presented a graphic of the estimated cumulative percent mass biodegraded with respect to each phase after Palmisano and Barlaz (1996) as Figure 2.2.

The cited literature indicates that approximately 35 to 40 percent of mass has been degraded by the start of the final phase of decomposition. Upon observation of the percent biodegraded measured by mass at the end of experiment the author concludes that the waste was in the final phase of decomposition as this work was concluded with greater than 40 percent mass degraded. This is further supported by gas composition studies performed at the end of the experiment which indicate gas profile to be similar to that observable during the final phase of decomposition.

5.7 Use of Loss on Ignition to Determine Percent Organic Solids

As indicated in Section 5.4, in lieu of the (C+H)/L, the author has proposed a correlation with loss of mass to determine state of biodegradation of the waste. Aside from the limitations of (C+H)/L, the author recognizes that the test is labor and time-intensive and currently only several labs are able to complete the test. This tends to constrain the ability of the end-market to obtain timely test results. The author recognizes the need to establish a test procedure which is repeatable as well as straightforward. Providing a test method which can be conducted by well-equipped geotechnical/environmental labs will increase the appeal of the more direct test method and ultimately the end use of this work.

To confirm the repeatability of this proposed test method, the author batched and tested a fresh sample of waste identical to the initial samples tested at inception of the experiment for percent organic solids. A test was run both on a sample with plastic (C-1a) and with plastics removed (C-1b). A second set of samples, both with plastics (C-2a) and without plastics (C-2b), were tested on the waste which had undergone some degradation.

The samples used for the second sample set were from the original C-2 bioreactor sample. When the bioreactor was decommissioned, a portion of the sample was frozen and the other portion was used for (C+H)/L testing. The frozen sample was thawed and used for this testing. The results of the testing are provided in Table 5.13.

Table 5.13 Determination and Comparison of Percent Organic Solids by Loss on Ignition

Sample No.	Pan Weight [g]	Pan + Dry Sample Weight [g]	Dry Sample Weight [g]	Pan + Dry Sample Weight [g] after burnoff	Dry Sample Weight after burnoff [g]	Weight Lost [g]	% Organic Solids (Measured By Shah)	% Organic Solids (Measured By Barlaz)
C-1a (With Plastics)	101.63	274.12	172.49	136.96	35.33	137.16	79.5%	-
C-1b (No Plastic)	103.59	238.45	134.86	132.82	29.23	105.63	78.3%	79.8%
C-2a (With Plastics)	104.23	252.83	148.60	151.45	47.22	101.38	68.2%	-
C-2b (No Plastics)	101.88	231.68	129.80	149.41	47.53	82.27	63.4%	61.6%

The percent organic solids measured by the author were compared against that obtained on comparable samples tested by Dr. Barlaz during (C+H)/L testing for this work. The testing results indicate similarity between the two independent analyses; therefore, the author believes that a level of repeatability can be readily achieved.

A variation is noted in the percent organic solids between the samples with plastics and those with plastic removed. As percent organic solids is defined as the loss of weight of organic matter divided by total sample weight, by removing plastics both the numerator and denominator are altered. Therefore it is expected that samples with plastic removed will has a lower reported percent organic solids through this method.

CHAPTER 6

DEVELOPMENT OF MODELS

6.1 Development of Gas Production Model

Multiple models were evaluated to determine the theoretical rate and quantity of gas production, and for determination of percent of biodegradation of the waste. The following models are presented and discussed to propose a model best-suited to predict gas production for mixed MSW waste.

6.1.1 Determination of Field-Observable Maximum Gas Generation using Natural Logarithmic Regression

The author employed the following procedure to determine the measurable end of biodegradation, characterized by a diminishing rate of gas production and indicating the substantial end of measurable biodegradation-related mechanisms. The procedure was also used during this experiment to validate the end of the experiment once gas flow meters registered no additional flow of methane gas. The author comments that the procedure could be similarly used in the field to determine the total actual quantity of gas that can be collected and to determine the time until substantial end of measurable biodegradation-related mechanisms.

The author used an analytical approach suggested by Raghu (2014) to determine the practical amount of gas which could be collected, and to extrapolate the gas production to determine the maximum gas which could be collected, $y_{max\text{-}actual}$, if the experiment was held until the end of biodegradation occurred.

In general, over 85 percent of the total actual maximum gas as predicted by this method which could be produced by the composite bioreactor was collected at the conclusion of the experiment.

To perform the analytical approach, the author plotted the daily rate of gas production versus time and cumulative gas collected versus time, as indicated in Figure 6.1 and 6.2. The author then determined the time at which the daily rate of gas production peaked, identified as time t_1. The cumulative gas, y_1, produced at time, t_1, was then determined from the cumulative graph. The gas production up to time t_1 can be characterized as the straight-line portion of the production curve, and can be separated from the evaluation of the exponential curve portion to determine the remaining gas capable of being produced, y'_{max}. The total gas, $y_{max\text{-}actual}$, which can be produced is then defined by Equation 6.1. The expression can be applied to both total landfill gas, or to the individual constituents of landfill gas such as methane or carbon dioxide. The author has provided calculations herewith based on methane gas to provide consistency with the data collected by flow meters.

$$y_{\max-actual} = y_1 + y'_{\max} \tag{6.1}$$

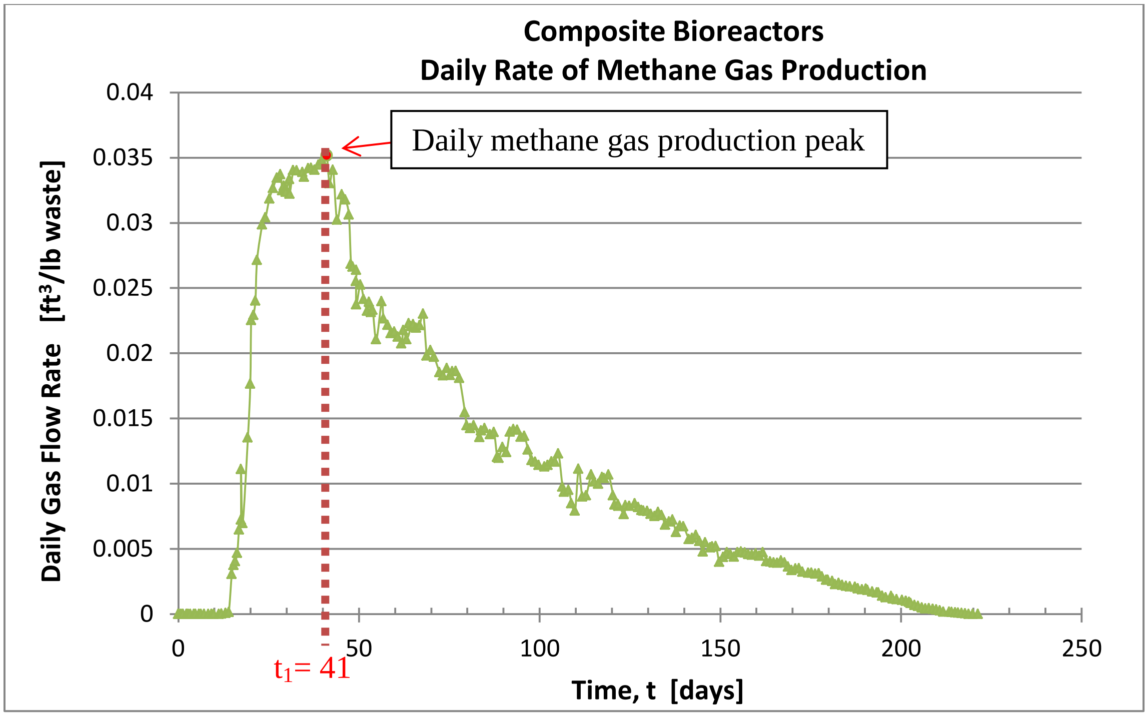

Figure 6.1 Daily Rate of Gas Production for Determination of End of Experiment

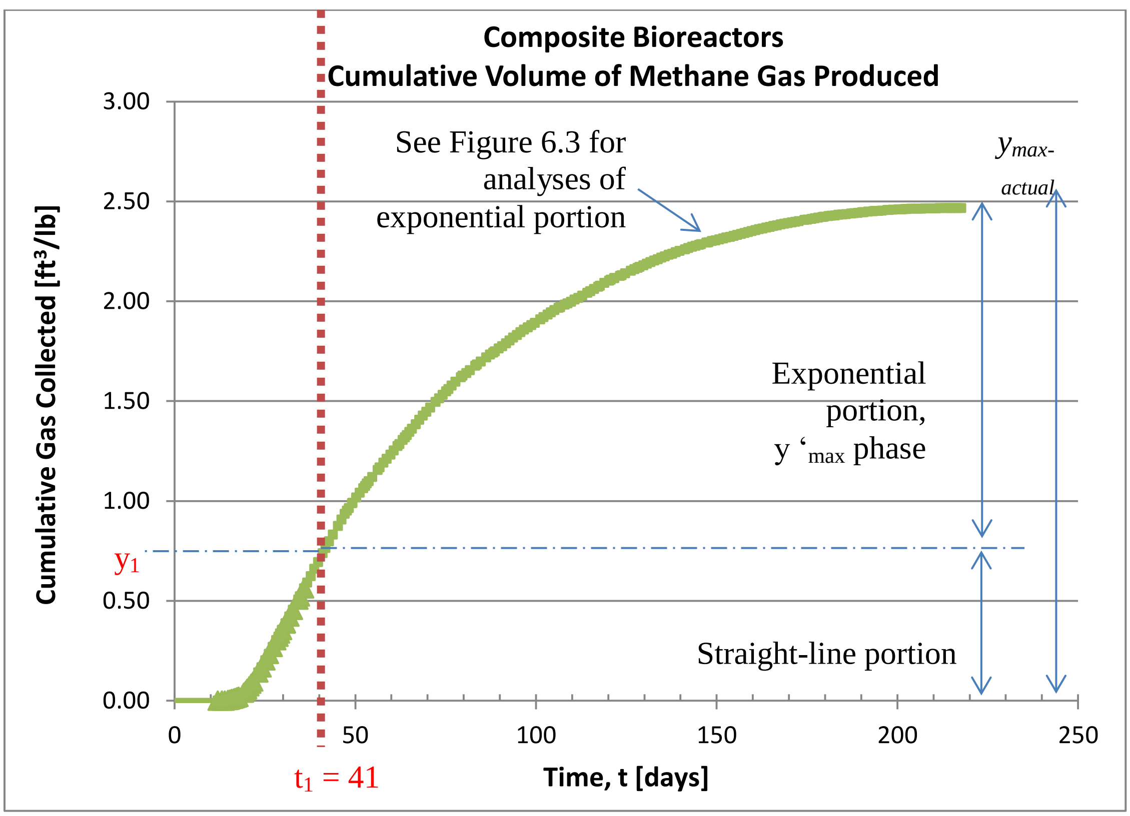

Figure 6.2 Cumulative Gas Production for Determination of End of Experiment

The exponential curve portion of data collected was evaluated by adjusting data ordinates to begin immediately after the straight-line portion where peak gas production had occurred. Adjusted dimensions are defined by Equation 6.2 and 6.3. The author subsequently created a plot of *y'* versus time after peak, T, as presented as Figure 6.3. The equation to the curve is expressed as Equation 6.4.

$$y' = y - y_1 \tag{6.2}$$

$$T = t - t_1 \tag{6.3}$$

$$y' = y'_{max} e^{-(K/T)} \tag{6.4}$$

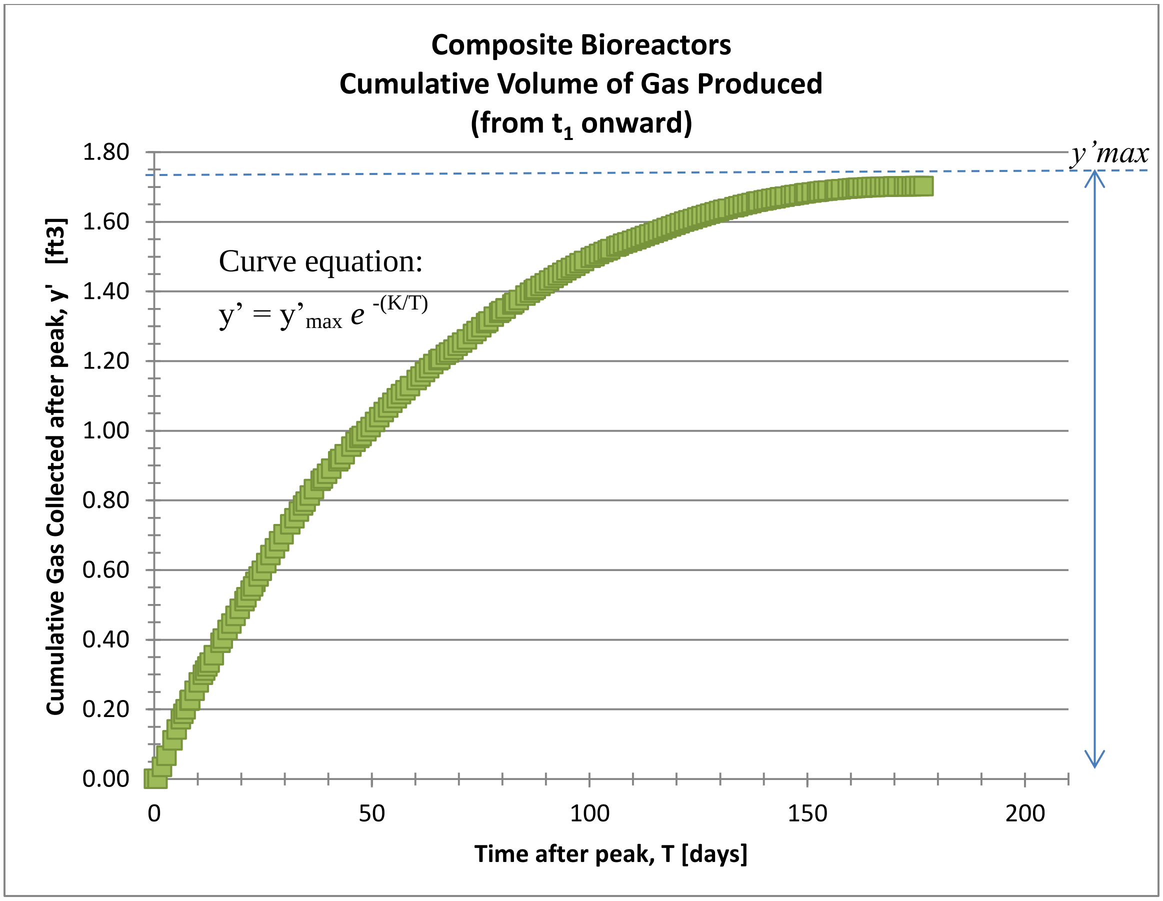

Figure 6.3 Cumulative Gas Production for Determination of End of Experiment

By taking the natural log of the gas production after peak ($\log_e y'$) and plotting against the inverse of T (1/T), a straight-line representation of data could be modeled as presented as Equation 6.5.

$$log_e y' = log_e y'_{max} - (K/T) \qquad (6.5)$$

A regression line of the data would determine the slope of the line, -K, which is proportional to the exponential half-life decay constant, k. Likewise the data would indicate the natural logarithm of the maximum gas capable of being produced, $\log_e y'_{max}$, determined when Equation 6.5 is equal to zero and intersects the x-axis. Figure 6.4 presents the evaluation of maximum actual gas recoverable for the composite bioreactor for this experiment.

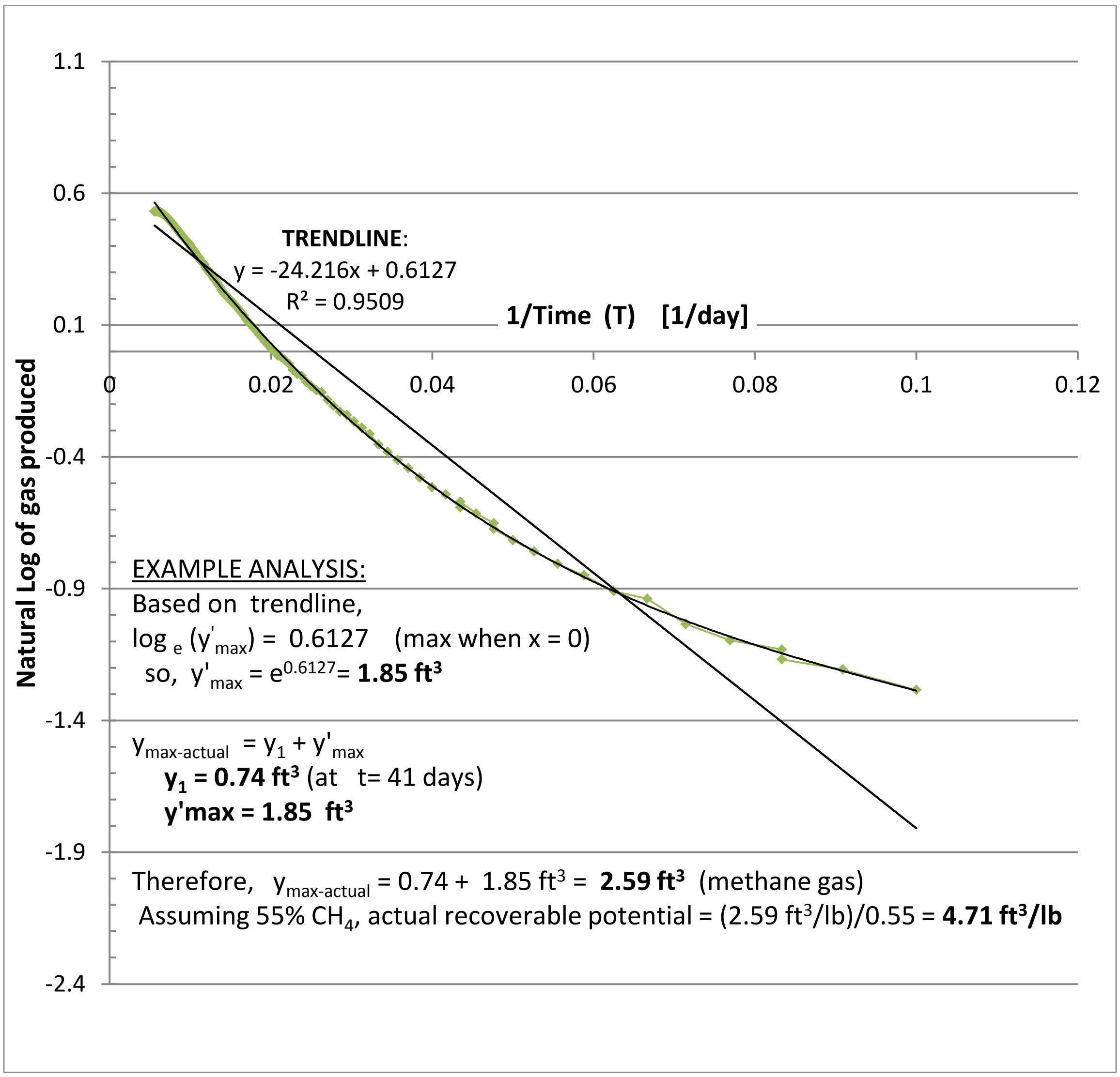

Figure 6.4 Determination of $y_{max\text{-}actual}$

Using the natural logarithmic method suggested by Raghu (2014), it was determined that the recoverable volume of methane gas which could be collected over a measurable timeframe is approximately 2.59 cubic feet per pound waste. Assuming a proportion of landfill gas consisting of 55 percent methane, the potential for actual total gas which can be collected is nearly 4.71 cubic feet per pound waste.

Based on the lambda method as modified by Lifrieri (2010), the computed theoretical total gas potential for composite bioreactors was 6.23 cubic feet per pound waste, or 3.43 cubic feet of methane per pound waste for a landfill gas with 55 percent methane proportion. At end of this experiment 2.55 cubic feet of methane gas, or 4.63 cubic feet of total gas, per pound waste were collected from the composite bioreactors. Therefore, approximately 74 percent of gas was collected at the conclusion of the experiment based on theoretical potential of 6.23 pounds per cubic foot. Based on a calculated total actual collectable methane gas of 4.71 pounds per cubic foot, as shown in Figure 6.4, 98 percent of actual gas was captured.

Calculations for the readily and moderately degradable bioreactor set are provided in Appendix G – Calculations to Determine Theoretical Gas Production and End of Experiment. Using the method shown above, the recoverable volume of captureable methane gas for the readily degradable bioreactor set was approximately 5.04 cubic feet per pound waste, or 9.17 cubic feet of total gas per pound waste. Calculation of the theoretical total gas potential by lambda method resulted in 4.97 cubic feet per pound waste, or 9.04 cubic feet of total gas per pound waste. At end of this experiment 4.62 cubic feet of methane gas, or 8.41 cubic feet of total gas, per pound waste were collected from the readily degradable bioreactors.

Therefore, approximately 93 percent of gas was collected at the conclusion of the experiment based on theoretical potential, or 92 percent of actual gas was captured based on calculated total actual collectable methane gas.

Similarly, the recoverable volume of captureable methane gas for the moderately degradable bioreactor set was approximately 3.32 cubic feet per pound waste, or 6.03 cubic feet of total gas per pound waste. Calculation of the theoretical total gas potential by lambda method resulted in 4.64 cubic feet per pound waste, or 8.44 cubic feet of total gas per pound waste. At end of this experiment 2.86 cubic feet of methane gas, or 5.2 cubic feet of total gas, per pound waste were collected from the readily degradable bioreactors. Therefore, approximately 62 percent of gas was collected at the conclusion of the experiment based on theoretical potential, or 86 percent of actual gas was captured based on calculated total actual collectable methane gas.

At the conclusion of the experiment, both the composite and readily degradable bioreactors had reached over 90 percent of their potential captureable gas, with the moderately degradable bioreactor recovering above 85 percent of its captureable gas. The author noted that gas flow meters indicated the methane flow through the flow meters were de minimis at this time; therefore the determination to conclude gas collection was made at this time. The recoverable volume of methane gas being near substantially captured and the lack of additional flow readings able to be registered on the gas flow meters supported the determination to end gas collection of the bioreactors.

The contribution due to the slowly degradable waste was neglected and not analyzed using this method since, compared to the readily and moderately degradable fractions, the gas collected by the slowly biodegradable bioreactors is less than 1.5% that by the readily and moderately degradable bioreactors.

6.1.2 Determination of Maximum Gas Generated Based on Degradable Mass

It is difficult to measure and predict field volumes change of a heterogeneous MSW material, as well as the change in mass. In the laboratory, under controlled conditions, changes in volume can be approximated continuously based on the volume of gas produced. The change in mass can also be obtained but only at discrete intervals and during destructive testing. In the field, it is difficult to obtain changes in mass as it requires exhuming waste samples and associated planning.

Biodegradation can be measured in two ways: 1) mass - directly from loss of weight of the degradable fraction, and 2) volume – from gas production and/or measurement of strain. Therefore, the author is primarily determining biodegradation based on volume, while using the change in mass at discrete intervals as a spot check. Unless otherwise stated, the biodegradation referred to in this work is based on volume. The author notes it is possible to achieve 100 percent biodegradation ideally based on mass; however, it is not possible to achieve 100 percent biodegradation based on volume for any waste containing inert matter. Definitions of percent biodegradation based on volume and mass are presented in Chapter 7.

The percent biodegradation based on mass is computed based on data obtained during the decommissioning process discussed in Section 5.5. The author used this information to draw a comparison to the data collected by the gas flow methods. Table 6.1 presents a comparison of the estimated percent biodegradation observed using several data sources obtained from this work. The "% Biodegraded, Weight Basis" is computed form decommissioning records summarized in Table 5.11. Theoretical maximum used for comparison corresponds to that computed by the Lambda method as outlined earlier.

The author notes that the percent biodegradation measured by weight basis may be overestimated, as the assumption is made that all loss of mass is due to complete conversion of biodegradable waste to landfill gases. It is the author's opinion that the constant process of leachate recirculation may contribute to dissolving of organic particles and physical breakdown. This physical breakdown would further allow the reduced particle size to be flushed and rinsed out of the system and be reported as loss of mass.

Additionally, although bioreactors were assembled with waste representing discrete categories corresponding to their rate of biodegradation, the author suggests that a portion of the waste may act at an intermediate rate and separate from the rate of the overall characteristic waste. For example food and yard waste, which are generally characterized as readily degradable, may have a portion of its waste acting as moderately or even slowly decomposable waste and thereby altering the assumption in which the waste acts homogenously as one type.

Table 6.1 Comparison of Percent Biodegradation Based on Loss of Weight and Volume of Gas Collected

Reactor Set	**% Biodegraded, Weight Basis**	**% Gas Collected Based on Theoretical by Gas Flow Meters Basis**	**% Gas Collected Based on Theoretical by Tedlar Gas Bags Basis**
Composite	71%	72%	85%
Readily	90%	93%	98%
Moderately	67%	62%	69%
Slowly	5%	-	1%

The author observes close agreement with percent biodegradation measured by mass compared against that computed based on gas collected by flow meters. Since percent biodegradation is based on theoretical gas production, it is the author's opinion that prediction of gas production is most accurately predicted by the lambda method as modified by Lifrieri (2010). The author notes that the slowly decomposable bioreactor set (which consisted of plastics) only lost 5 percent of its average mass during the same period when the composite, readily, and moderately degradable were substantially decomposed and lost 71, 90, and 67 percent mass, respectively, as measured at the end of the experiment. Therefore, the readily and moderately degradable waste fractions contribute to substantial amount of settlement. Thus, for the purposes of analyzing MSW landfill waste, the contribution of settlement due to slowly degradable wastes may be neglected.

6.1.3 Development of Waste-Specific Gas Generation Curve Using Decay Rate Constants

It is one of the intents of this work to create a gas production model which accounts for the variability of a composite sample, and of waste of any composition. Gas production models with a single first-order decay rate, "k", are currently the state-of-practice and used in the EPA LandGEM model accepted by industry.

It is the author's opinion, as well as that of several others (Findikakis et. al 1979, Durmesoglu et.al 2005, Lifrieri 2010), that the single decay constant used in gas production modeling is inefficient to represent the biodegradation of MSW. This is a result of waste inherently consisting of a heterogeneous mixture of materials with different levels of biodegradability. Total gas production from mixed MSW can be expressed as the combination of gas produced by each piece of waste, at an elemental basis. Comprehensively, the individual waste items may be grouped and categorized by the readily, moderately, and slowly degradable descriptors defined herein this work; therefore, the total gas volume produced, V_t, can be expressed proportional to the gas produced by each waste type category. This is expressed as Equation 6.6. The inert fraction is not included because it does not produce gas.

$$V_t = V_r + V_m + V_s \tag{6.6}$$

From this understanding, the author hypothesizes that an overall decay constant modifier for a mixed MSW sample, k_c, could be determined by characterizing the mixed waste into representative fractions of readily, moderately, and slowly biodegradable components, as well as inert fraction and multiplying by respective decay modifiers to obtain an overall, waste-specific single decay modifier for the specific waste type. The hypothesis is expressed as Equation 6.7.

$$k_c = n_r k_r + n_m k_m + n_s k_s \tag{6.7}$$

In the expression, n_r, n_m, and n_s represent the percent of waste of readily, moderately, and slowly biodegradable waste fraction comprising the composite basis. Derivation of Equation 6.7 from Equation 6.6 is provided in Appendix F – Derivation of Equations.

Using the above basis, the author graphically plotted the data obtained from gas flow meters for the composite, readily, and moderately degradable bioreactor sets. The graphic is shown as Figure 6.5. It is noted that the gas generation from the slowly degradable bioreactor set is not visible on the graphic, as the flow of gas is magnitudes of scale lower in comparison to the other fractions. Additionally gas generation data from the slowly degradable bioreactor set was collected using tedlar gas bags; therefore, daily methane gas generation must be approximated based on the limited data available.

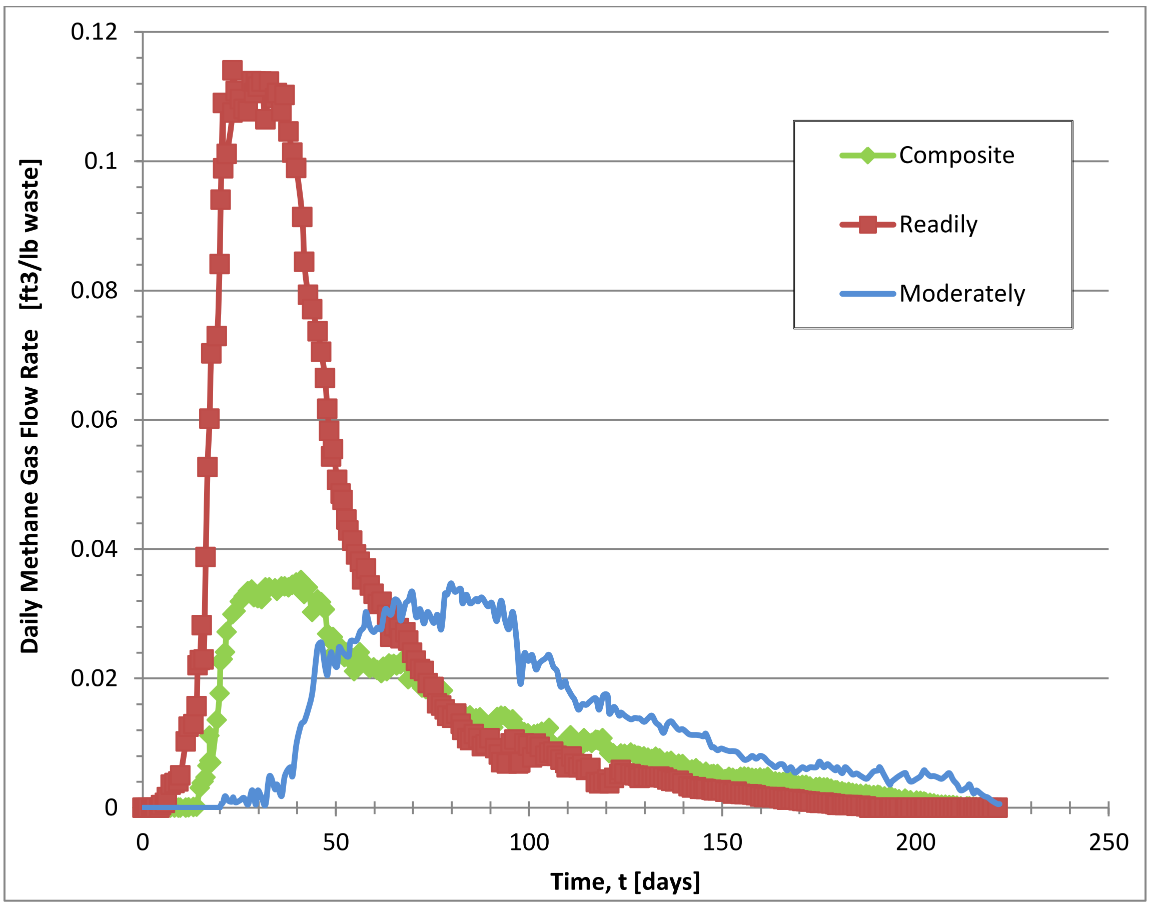

Figure 6.5 Comparison of Daily Methane Gas Flow Rate Obtained By Composite, Readily, and Moderately Degradable Methane Gas Flow Meters

Subsequently, for the composite waste tested during this experiment consisting of 25 percent readily decomposable fraction, 43 percent moderately decomposable fraction, and 12 percent slowly decomposable fraction, the author plotted data obtained from the composite gas flow against a calculated gas flow curve based on proportion of wastes and readily and moderately gas flow meter data. The graphic is shown as Figure 6.6. The author believes that the calculated gas generation curve is in close agreement with the actual gas generation curve obtained from flow data for the composite bioreactor set. An independent confirmation of this was performed data provided by Lifrieri (2010). Both confirmed that the method of superposition is applicable.

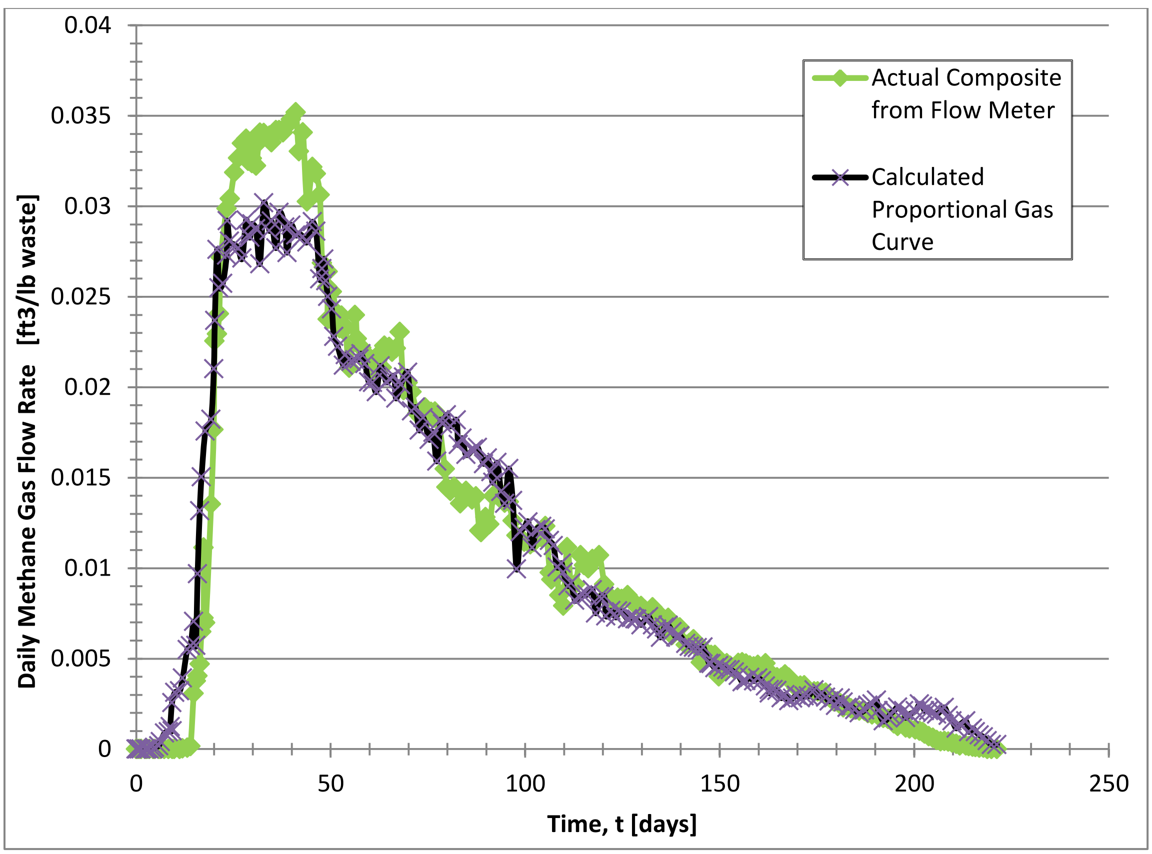

Figure 6.6 Comparison Of Calculated And Actual Daily Methane Flow Rate For Composite Waste

The author completed a sensitivity analysis, varying the proportion of readily degradable waste by 5 percent above and below the composition evaluated, and conversely decreasing and increasing the proportion of moderately degradable by 5 percent, respectively, to understand the influence of a minor adjustment caused by changes in waste stream and composition. Figure 6.7 indicates the results of the sensitivity analyses conducted for both the upper and lower bound. The author comments that the results from the upper bound are in very close agreement with those from the actual observed actual gas collected based on the composite gas flow totalizer. Therefore, a minor adjustment of even 5 percent may create a better fit or influence the calculated peak gas flow rate.

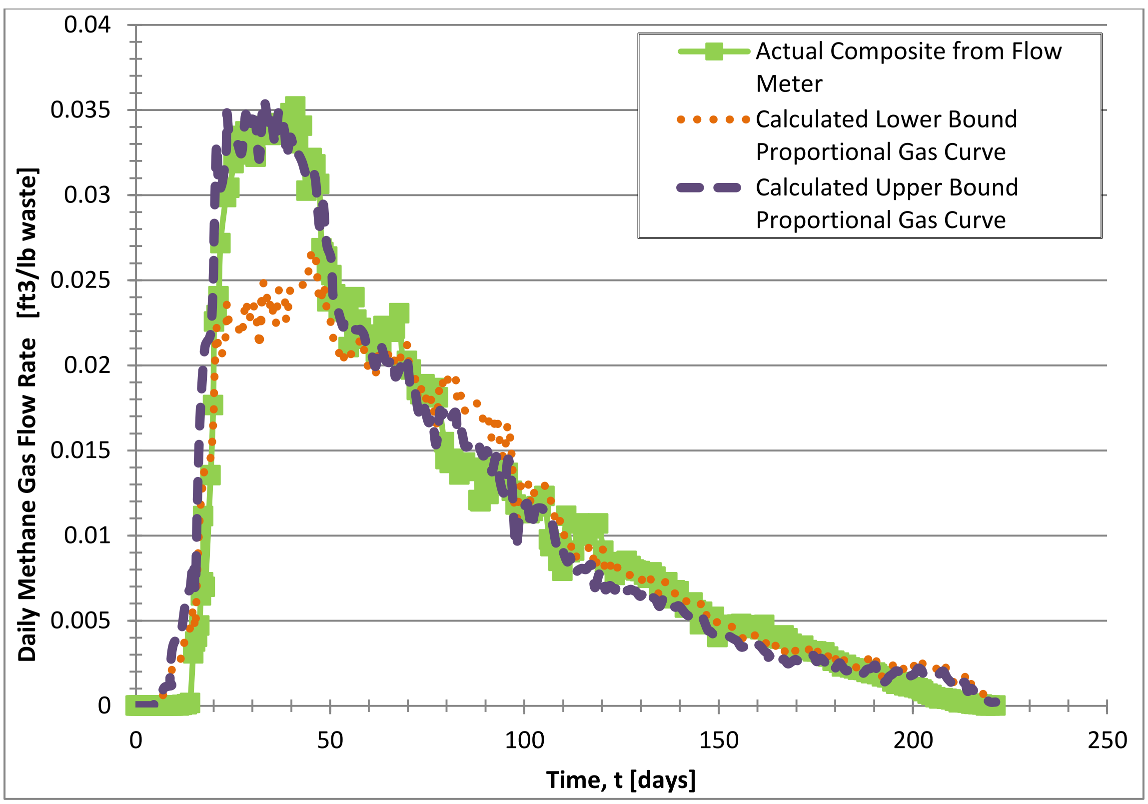

Figure 6.7 Lower Bound And Upper Bound Sensitivity Analyses Comparison To Actual Daily Methane Flow Rate For Composite Waste

The author observes that the limitation of generalizing waste into three discrete categories (readily, moderately, slowly biodegradable) forces the assumption that the waste will act only at the rate of decomposition assigned to one of the three waste types, and that no portion of the waste will act at an intermediate rate. For example, all constituents of the readily degradable fraction are assumed to act at the single decay constant assigned for the readily degradable waste. As waste is inherently heterogeneous, different portions of the waste will decompose at a variable rate; therefore the author recommends performing sensitivity analyses on the waste composition to create an upper and lower-bound value for the single decay constant modifier, k_c, when employing the method in practice.

The author further tested the hypothesis of superposition by evaluating component modifiers obtained from measurements of actual total gas collected as indicated in Section 5.2. Using Figures 5.10, 5.12, and 5.14 for readily, moderately, and slowly degradable bioreactor sets, respectively, component modifiers based on total gas production of 0.045, 0.012, and 0.0021 $year^{-1}$ are obtained for each of the respective bioreactor sets. Using the waste profile for composite waste, a calculated composite decay modifier, k_c , of 0.0167 $year^{-1}$ can be obtained. This is in close agreement with the observed actual composite k of 0.0170 $year^{-1}$ from the composite bioreactor. A similar agreement was achieved from the data collected by Lifrieri (2010) as discussed earlier.

It is therefore the author's opinion that a waste-specific, single decay constant modifier can be created by combining the individual, proportioned decay rates of each material class as confirmed by the observations of this work.

The above work provides support that the theory of superposition is a viable assumption even given the variations in waste types and inherent heterogeneity of operating conditions and waste types for landfill.

6.1.4 Determination of Half-Life Coefficients and Discussion of Half-Life Gas Generation Curve

As discussed in Section 3.3, Findikakis and Leckie (1979) developed the first model to relate the half-life decay concept to landfill gas production. Subsequently, Durmusoglu et al. (2005) produced a similar variation of the original model and introduced the concept of the total gas production rate to develop both the gas remaining and the cumulative gas production through the use of the lambda method. The lambda method was further refined by Lifrieri (2010), and was used to determine a more accurate model for theoretical gas potential as a function of time.

This author clarifies that the half-life decay modifiers proposed by Findikakis are not directly comparable to the single decay constant discussed in Section 6.1.3, as Findikakis' modifiers are based on waste half-life and are obtainable by plotting the inverse of the cumulative gas production curve (gas remaining) versus time. The single decay constants developed in Section 6.1.3 are obtained by plotting daily gas production and curve-fitting the exponential decay of the gas production from the time of peak gas production and onward. The single decay constant concept is more closely relatable to that utilized by industry-standard EPA LandGEM model. Therefore, the author emphasizes a differentiation between the variables, with single decay constants identified as k_c , k_r , k_m , and k_s and half-life decay modifiers as λ_c, λ_r , λ_m , and λ_s for composite, readily, moderately, and slowly degradable waste categories, respectively.

In the field, half-life is arrived using recommendations by multiple authors (Reinhart and Barlaz 2010, Barlaz et. al 2009, Pacey et. al 1996, USEPA 2003, Waste Management 2012, Metha et. al 2002) based on the required closure period for a landfill, or the time at which "substantial decomposition" has completed. The author clarifies that "substantial decomposition" is defined as complete degradation of readily degradable fraction, and considerable decomposition of moderately degradable fraction. The time at which this occurs does not indicate the point when all waste has reached practical end of decomposition.

The author explains this by using an example of the components within the moderately decomposable waste fraction which consist of various newsprint and paper products. A portion of these constituents, such as glossy magazines, coated and treated wood, and textiles have covered fibers will take longer to reach decomposition than those products which have exposed fibers such as raw wood, newsprint, and office paper. Therefore, although complete decomposition of all of these constituents may not occur by the end of the closure period, the rate at which these remaining constituents decompose and gas is produced is slower than during the closure period.

For a traditional landfill, the closure period is well-defined in industry as 30 years. This 30 year closure period corresponds to a half-life decay constant equal to 0.023 $year^{-1}$. Numerous sources within the United States (USEPA 2005, 2010) and internationally (EC 2006) recognize the state-of-the practice and understanding of this 30 year half-life time for traditional landfills and suggest a half-life decay constant between 0.02 $year^{-1}$and 0.04 $year^{-1}$ (USEPA 2005). The solid waste industry (Waste Management

2005) likewise also corroborates these recommendations through field observations conducted across over 78 landfills across the United States and internationally.

During his work, Lifrieri (2010) performed iterative analyses on waste half-life using decay factors suggested by Findikakis and Leckie (1979) and Durmesoglu et. al (2005) to determine the percent biodegradation of a sample at various years and determine the theoretical time to complete end of biodegradation. Based on his work, at 30 years, the theoretical percent biodegradation is 49.7 percent for a composite waste sample with similar waste composition tested herein. This additionally supports the understanding that the theoretical half-life of a traditional MSW landfill is approximately 30 years.

The author clarifies that, although the closure period theoretically represents half-life of the waste, observation of gas recovery and settlement readings may suggest a greater practical percent decomposition such as 75 to 90 percent biodegradation. The author notes that the explanation for this is similar to the field-observable maximum gas generation concept suggested in Section 6.1.1 of this work.

Additionally, in a laboratory environment, the efficiency of gas collection systems can be 90 percent or higher (De la Cruz and Barlaz, 2010); however field-efficiency of gas recovery systems may vary between 5 to 50 percent (Barlaz et. al 2008, Reinhart and Barlaz 2010, SCS Engineers 1997). Variability in recovery efficiency can be attributed to landfill geometry and environment, such as liner and cover materials, cover maintenance, design and installation of gas extraction systems, and other factors. In a comparison of gas extraction system efficiencies undertaken by SCS Engineers (1997) it was noted that the principal reason for landfills with low efficiency systems was that methane recovery was not maximized, and that only enough landfill gas was recovered to support low-power energy equipment.

Therefore, although the theoretical half-lives for a traditional landfill and bioreactor landfill are 30 years and between 8 and 15 years, respectively, practically this may be beyond t_{50} as expected by gas production as the efficiency of the system will only allow a recovery of a portion of the gas produced.

On the characteristics of a bioreactor landfill, De la Cruz and Barlaz (2010), Barlaz et. al (2008), and Hossain (2003) conducted studies to compare between the behavior of a traditional landfill and bioreactor landfill. Although the total quantity of gas which can be produced is identical for either method, the rate at which gas production and waste stabilization occurs for a bioreactor landfill is more rapid than that of a traditional landfill. The author has provided background regarding this in Section 3.1. Figure 3.1 depicts the traditional landfill gas production curve and a more peaked, narrow bioreactor landfill gas production curve.

The work conducted by the abovementioned researchers found that the gas decay constant (“k”) for a bioreactor landfill is between two and three times that of a traditional landfill. Barlaz et. al (2010) and Tolaymat et. al (2010) recommend a decay rate of between 0.04 $year^{-1}$and 0.08 $year^{-1}$for landfills that are wetter than normal or have some leachate circulation (most landfills), and between 0.08 to 0.12 $year^{-1}$ for bioreactor landfills. Both groups of researchers recognize expert judgment must be utilized when selecting the decay constant for bioreactor landfills, as the rate constant of 0.12 $year^{-1}$ is for ideal and accurately controlled conditions. The national average for all landfills based on expert judgment is closer to 0.052 $year^{-1}$ (EPA 2010). Using an average wet decay rate constant of 0.06 $year^{-1}$ and an average bioreactor decay rate constant of 0.1 $year^{-1}$, the corresponding half-life for a bioreactor landfill is between 7 and 11 years.

Several authors including Pacey et. al (1996), USEPA (2003), and Metha et. al (2002), have suggested the half-life period for a bioreactor landfill is between 10 to 15 years. Industry (Waste Management, 2005) and practicing professionals in the solid waste consulting field (SCS Engineers, 2014) likewise suggest a closure period of 10 to 15 years for bioreactor landfills. Based on a half-life of 30 years for a traditional landfill and the sources captioned above, the author suggests it is not unreasonable that the half-life of a bioreactor landfill can then be between 8 and 15 years.

For this work, the half-life decay modifier, λ, is calculated by determining the time for waste half-life, and successively by first-order kinetics using Equation 3.8. By plotting the total gas remaining as a function of time, the author computed the time at which 50 percent of theoretical gas potential is collected, or the time for waste half-life. The author has presented this graphically as Figure 6.8, Figure 6.9, Figure 6.10, and Figure 6.11 for the composite, readily, moderately, and slowly degradable bioreactors, respectively.

The half-life decay modifiers can also be directly calculated by plotting the total gas remaining as a function of time and curve fitting an exponential decay regression across the data. The exponent variable observed from the regression is then the directly calculated half-life decay constant. The author has presented this technique graphically as Figure 6.12, Figure 6.13, Figure 6.14, and Figure 6.15 for the composite, readily, moderately, and slowly degradable bioreactors, respectively.

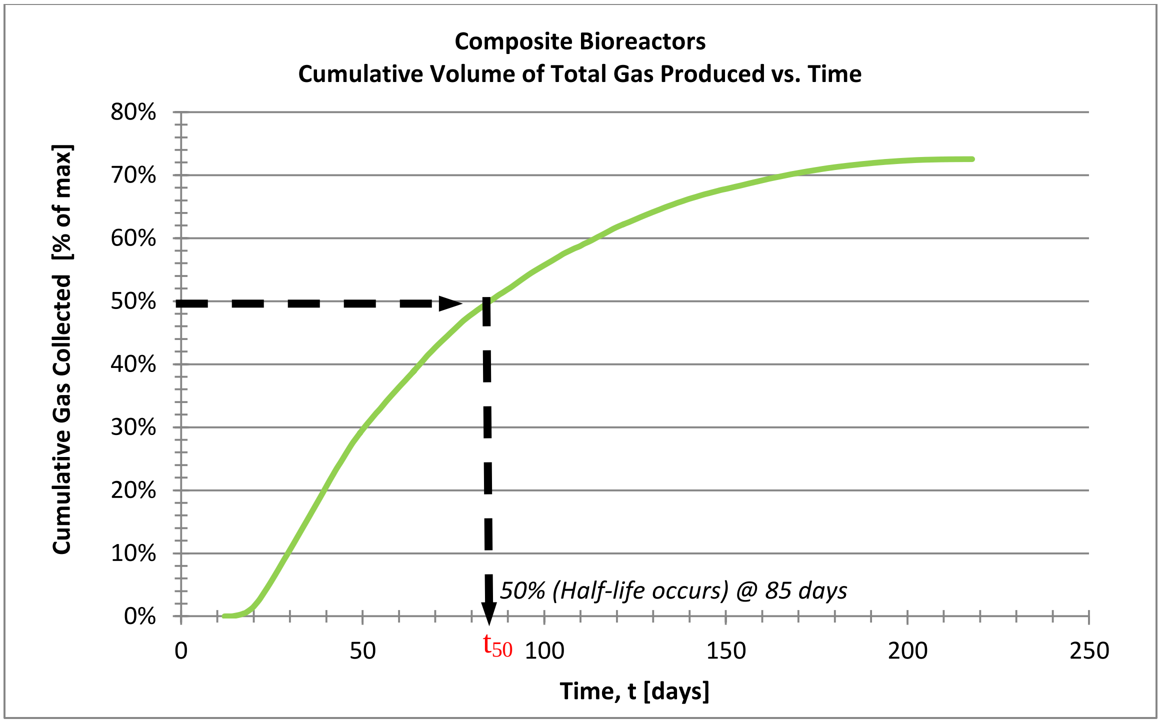

Figure 6.8 Determination of Half-Life Time Based on Percent Total Gas Collected for Composite Bioreactors

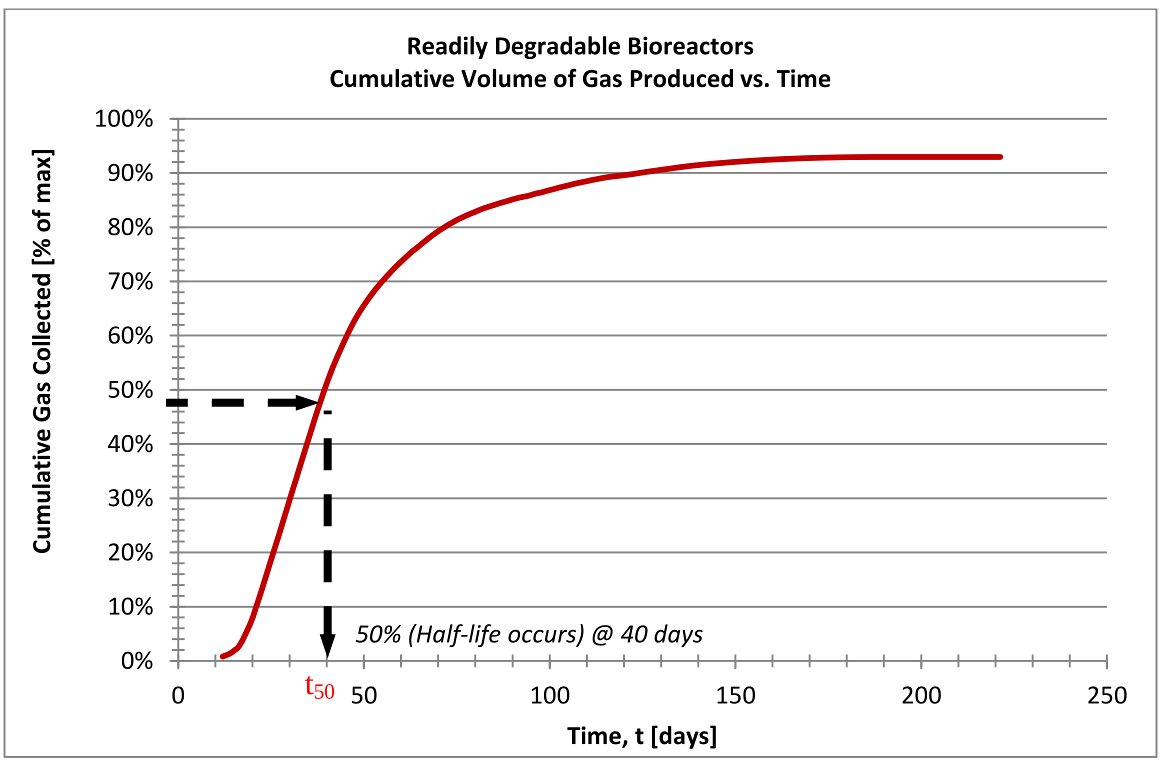

Figure 6.9 Determination of Half-Life Time Based on Percent Total Gas Collected for Readily Degradable Bioreactors

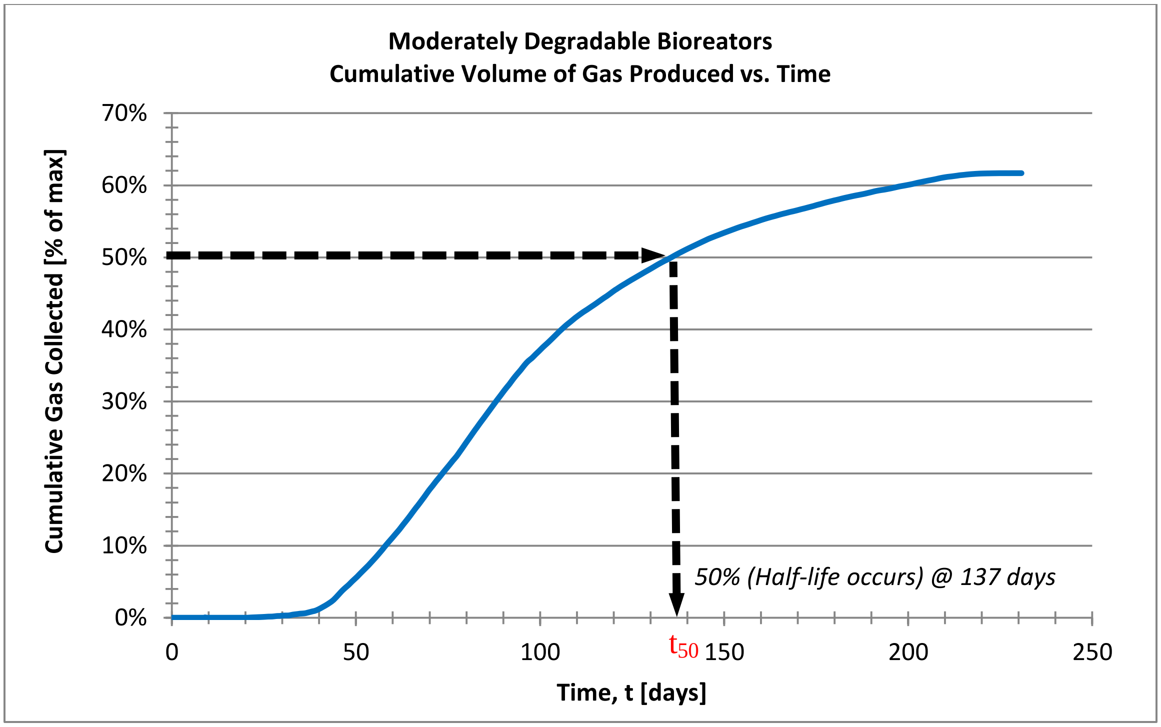

Figure 6.10 Determination of Half-Life Time Based on Percent Total Gas Collected for Moderately Degradable Bioreactors

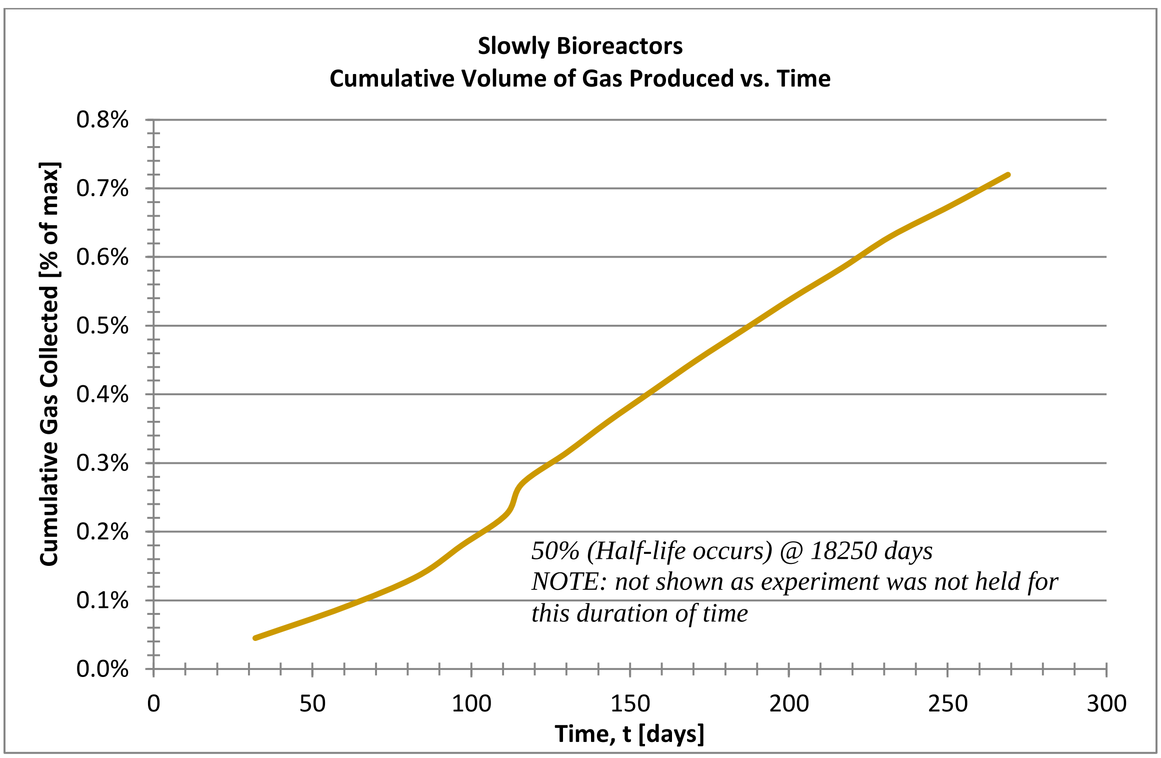

Figure 6.11 Determination of Half-Life Time Based on Percent Total Gas Collected for Slowly Degradable Bioreactors

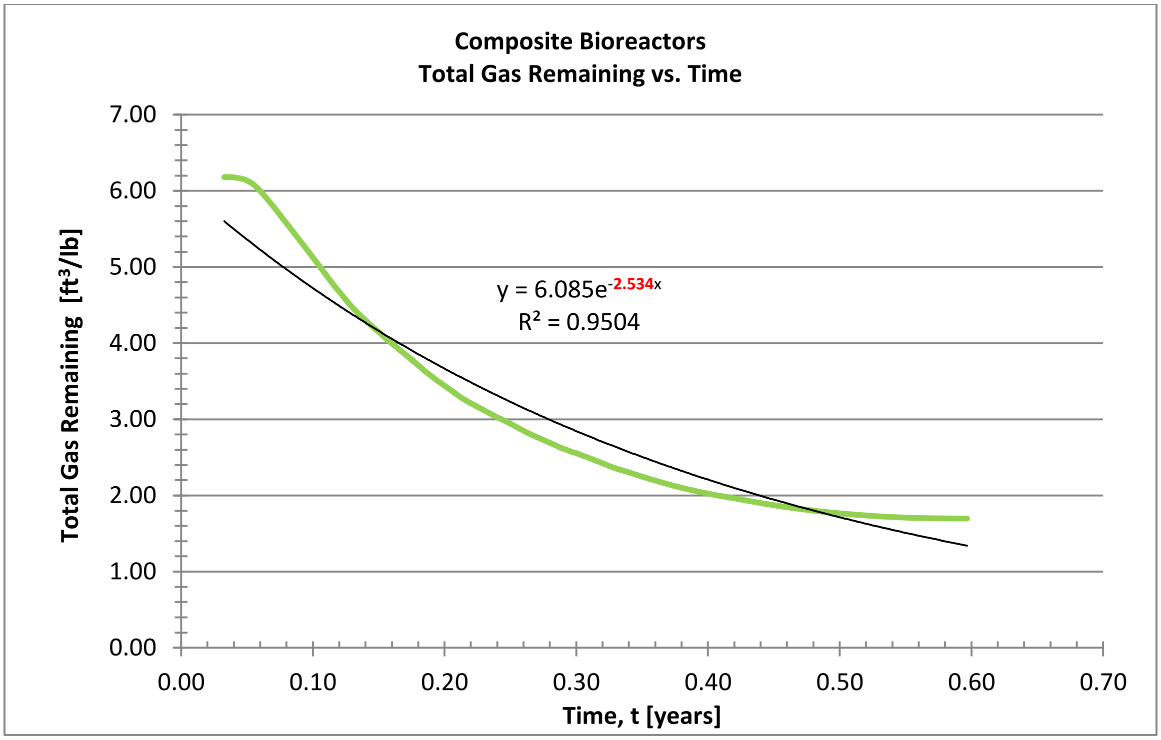

Figure 6.12 Determination of Calculated Half-Life Decay Constant Based on Total Gas Remaining for Composite Bioreactors

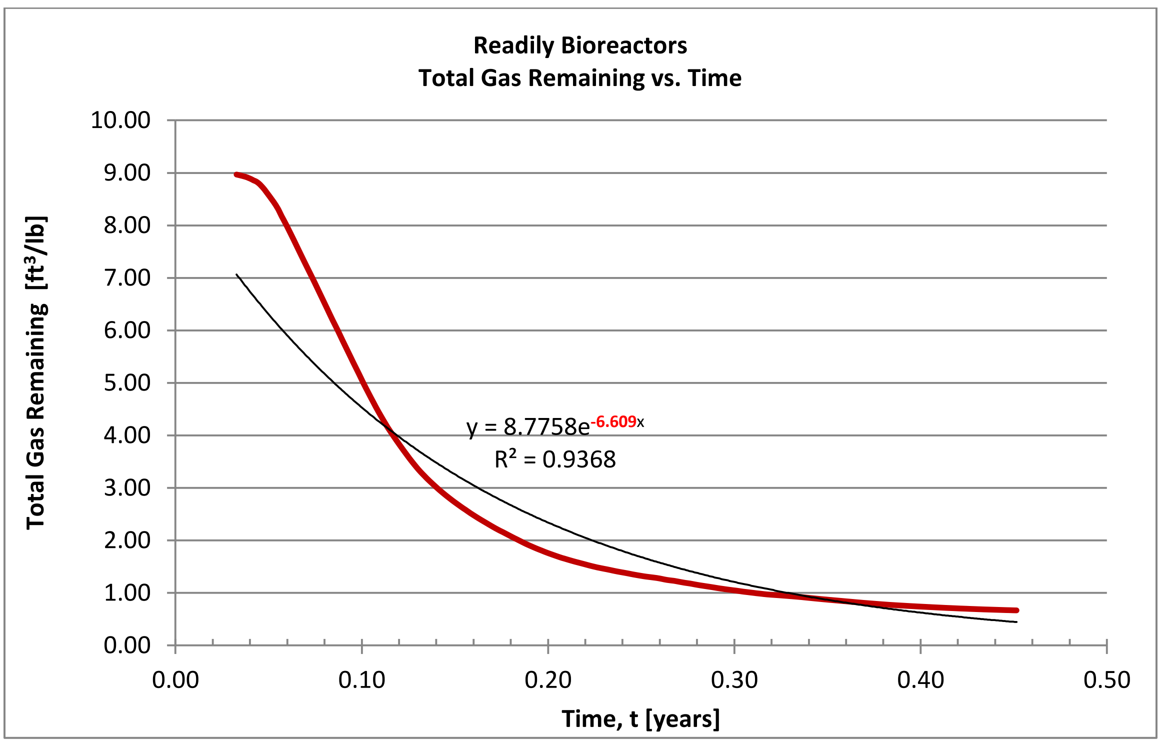

Figure 6.13 Determination of Calculated Half-Life Decay Constant Based on Total Gas Remaining for Readily Degradable Bioreactors

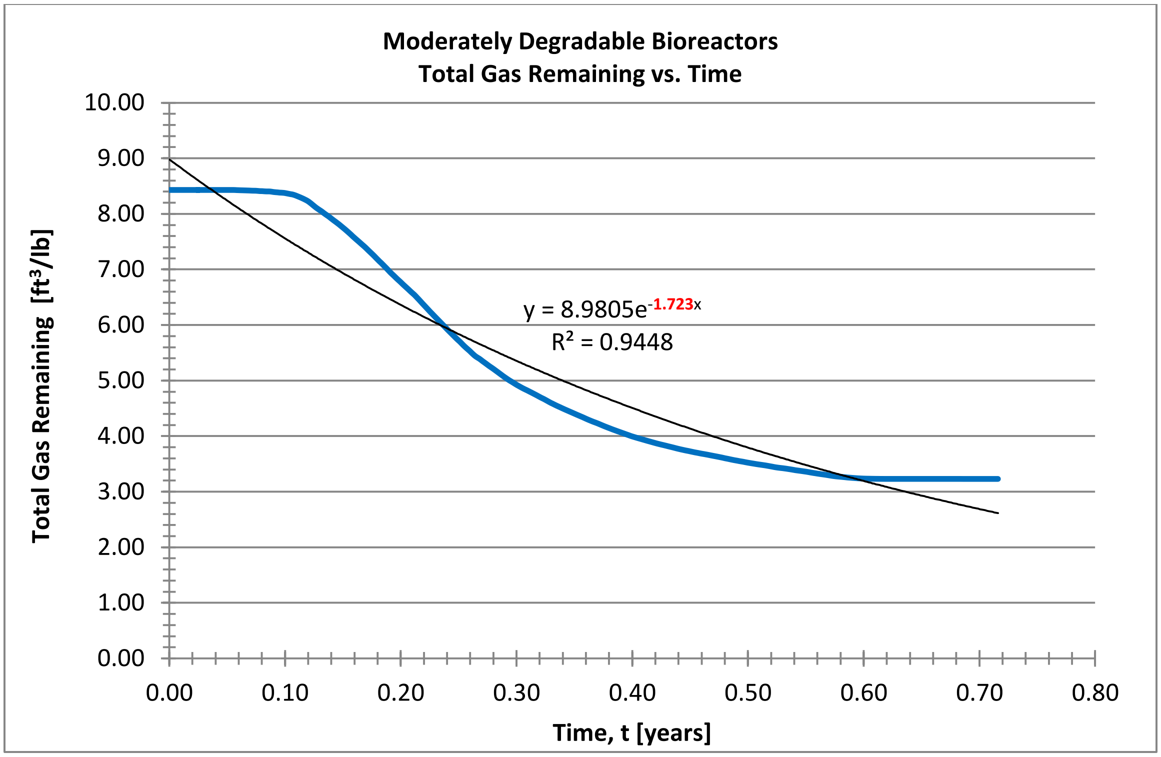

Figure 6.14 Determination of Calculated Half-Life Decay Constant Based on Total Gas Remaining for Moderately Degradable Bioreactors

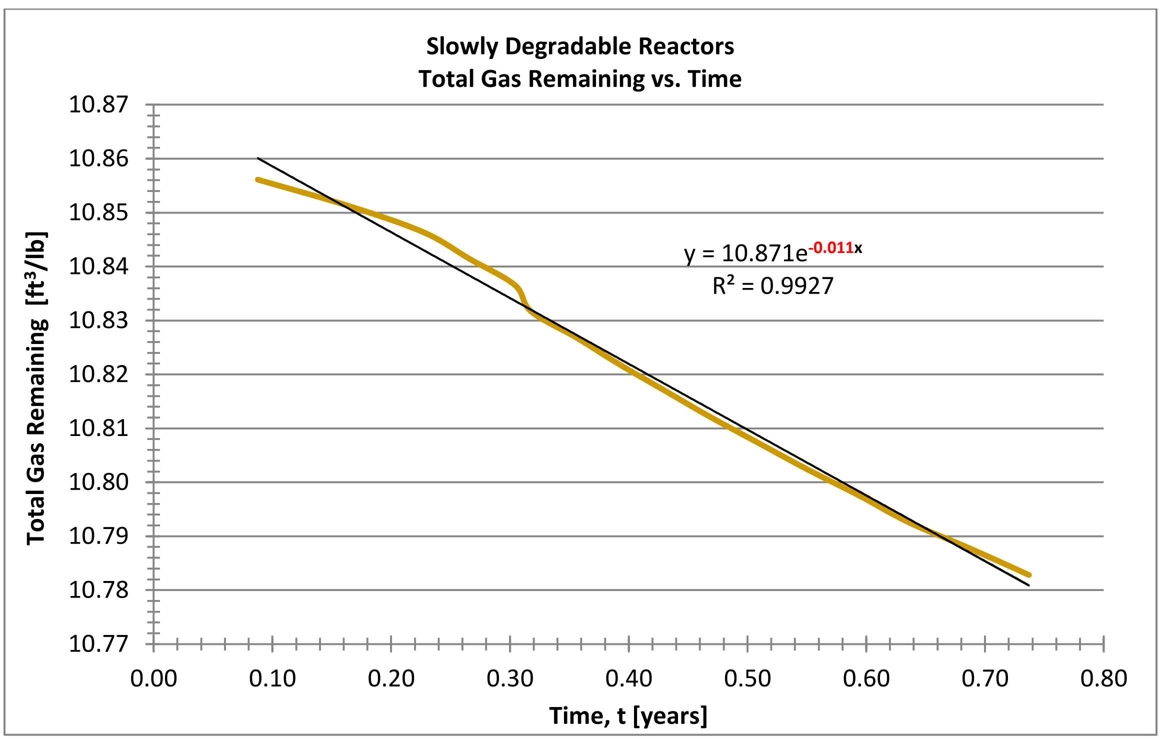

Figure 6.15 Determination of Calculated Half-Life Decay Constant Based on Total Gas Remaining for Moderately Degradable Bioreactors

The author has provided Table 6.2 to present the results of the analyses and provide a comparison of the half-life decay constants computed. Using half-life decay modifiers of 6.609, 1.723, and 0.011 year^{-1} for the readily, moderately, and slowly degradable bioreactor sets, respectively, and the waste profile for composite waste, a calculated composite half-life decay modifier, λ_c , of 2.394 year^{-1} is obtained. This is within 5 percent of the observed actual λ_c of 2.534 year^{-1} from the composite bioreactor. The author notes that is only an approximate method since the weighted average concept will apply for the exponential portion of the rate of gas generation versus time graph, and the straight line portion is not considered. Therefore a variation, such as the 5 percent observed above, is observed for the waste tested in this study.

Table 6.2 Summary and Comparison of Calculated Half-Life Decay Constants

Reactor	**Assigned Half-Life Constant, λ_n**	**t_{50} for 50% gas [days]**	**t_{50} [year]**	**k_{lab}, gas production decay constant [year^{-1}]**	**λ_n, Half-Life constant suggested Findikakis (1979)**	**λ_n, gas production decay constant [year^{-1}] from graphical method**	**Proportion of Waste**	**Proportional λ**
Composite	λ_c	85	0.233	2.980	-	2.534	-	-
Readily	λ_1	40	0.110	6.320	0.139	6.609	25%	1.652
Moderately	λ_2	137	0.375	1.850	0.023	1.723	43%	0.741
Slowly	λ_3	18250	50	0.010	0.017	0.011	12%	0.0013

The author comments that a comparison to the half-life decay modifiers suggested by Findikakis and Leckie (1979) and Durmesoglu (2005) is included in the summary provided as Table 6.2.

6.1.5 Discussion of Laboratory and Field Values of Lambda

Upon review of the data, a substantial difference is noted between the two. It is understood that the half-life times and half-life modifiers by Findikakis are based on field conditions, whereas those which are calculated herewith evaluate the waste in a controlled laboratory condition. Under field conditions, the effects of sample size, heterogeneity of waste, movement of landfill gases, environment, and other factors are amplified, which influence the quantity and rate of gas production and therefore the resulting waste half-life. This is corroborated by several authors (Barlaz et al. 1990) who have noted that actual full-scale landfill gas collection records indicated lower yields and rates of gas production in comparison to laboratory estimates.

Additionally, the author remarks that the half-lives suggested by Findikakis are for raditional landfills, while this author's work is conducted to simulate a bioreactor landfill with enhanced capacity to accelerate the rate of biodegradation. The nature of the bioreactor environment inherently suggests that the waste would degrade at an accelerated rate, thereby decreasing the waste half-life time and increasing the half-life decay modifier as shown by this work. This is supported by multiple authors, including Hossain (2003), Pohland and Kim (2003), USEPA (2003), Reinhart and Townsend (1998), and Pohland and Al-Yousfi (1994), with additional background provided in Chapter 3. Therefore, the modifiers presented by Findikakis (1979) and successively promoted by Durmesoglu (2005) to determine the rate of gas production would not be applicable for use in this study. However, the total quantity of gas using the modifiers at end of decomposition should be similar. The work completed herein supports the above contention.

Half-life decay constants obtained from gas collection records from such bioreactor or leachate recirculation landfills in operation for 15 years or longer would be applicable to this work.

6.1.6 Discussion of Preferred Gas Production Model

As the author has evaluated several methods to determine theoretical gas potential herein this work, Table 6.3 is provided for a comparison of the results compiled through the evaluation of various models.

Table 6.3 Comparison of Theoretical Gas Potential for Various Methods

Method (Listed Highest to Lowest Composite Potential)	**Theoretical Gas Potential [ft^3/lb waste]**			
	Readily	**Moderately**	**Slowly***	**Composite**
Stoichiometry (Ham et. al 1979, Tchobanoglous 1993, Barlaz 1990)	11.89	12.00	13.22	9.75
Half-Life Decay Modifiers (Findikakis 1979, Durmusoglu 2005)	9.40	14.10	7.83	9.35
Mass Degradation (Shah 2015)	9.31	7.75	5.70	6.35
Modified Lambda Method (Lifrieri 2010)	9.04	8.27	11.29	6.23
Modified SIMCON Model (Raghu and Gausconi 2002)	-	-	-	5.58
LandGEM Model (EPA 2005)	-	-	-	5.45
Natural Logarithmic Regression - y_{max} (Shah 2015)	9.17	6.03	12.80	4.47
AVERAGE - ALL METHODS	9.76	9.63	10.17*	6.74
*Note: *Please refer to discussion in next paragraph*				

The author and several others (Shah et. al 2007, Ishigaki et al. 2003, Tchobanoglous 1993, Albertson et. al, 1987) note the inability to directly use of stoichiometric and mathematical models to predict the gas for plastics (noted with asterisk above). Models for plastic, which comprise the “slowly degradable” composition waste used during this research, greatly overestimate the theoretical gas production. As the nitrogen content of plastics is diminutive in comparison to other elements, normalization with respect to nitrogen will produce an elemental expression of the waste with exaggerated proportions of carbon, hydrogen, and oxygen, and thus an overestimated theoretical gas production.

It is observed that theoretical gas production for slowly decomposable wastes is most accurately described by comparison of total gas collected and measurement of actual mass degradation. Ishigaki et al. (2003) suggest that actual theoretical gas production of plastics is between 30 to 50 percent of the calculated stoichiometric potential, which this author has evaluated to be 13.22 cubic feet per pound waste. The theoretical potential of 5.70 cubic feet per pound waste predicted by this author based on mass degradation falls within the range of 3.97 and 6.61 cubic feet per pound waste suggested by Ishigaki et al.

Similarly, it was previously concluded by this author that the method of superposition is a viable assumption to predict the total gas potential and rate of decomposition. As such, utilizing the composite waste profile evaluated during this work consisting of 25 percent readily, 43 percent moderately, 12 percent slowly decomposable waste, and remaining inert matter, an average calculated theoretical gas potential for the composite waste can be produced for each method.

Table 6.4 evaluates these calculated composite gas potentials based on various methods. For a specific waste utilized in this study, the results of this comparison indicate an average calculated theoretical gas potential of 6.93 cubic feet per pound waste, which is within 3 percent of the average of all methods directly predicting the theoretical composite gas potential. However, the author notes that the method of superposition to predict total gas potential gives a general estimate for total gas potential of a composite waste. This is due to the limitations of using weighted modifiers for calculating composite lambda (half-life constant) as presented earlier.

Table 6.4 Comparison of Calculated Theoretical Gas Potential for Composite Waste Based on Various Methods

Method (Listed Highest to Lowest Potential)	**Computed Theoretical Gas Potential for Composite Waste Based on Proportions [ft^3/lb waste]**
Average of "AVERAGE - ALL METHODS"	7.80
Modified Lambda Method (Lifrieri 2010)	7.17
Natural Logarithmic Regression - y_{max} (Shah 2015)	6.42
Mass Degradation (Shah 2015)	6.34
Average from all calculated Composite:	**6.93**

It is the author's opinion that a joint evaluation of both actual gas produced and actual mass degraded is the best way of predicting gas production and time remaining for end of decomposition. However, the author understands this may work only in a laboratory environment as the difficulty of collecting all landfill gas produced and regulatory constraints associated with exhuming waste from a landfill may prohibit the practicality of making such measurements.

In Table 6.1, the author compares the percent biodegraded based on actual mass degraded to percent of gas collected based on a theoretical gas potential by the lambda method as modified by Lifrieri (2010). It is the author's opinion from the comparison that the two methods produce results within a 15 percent range. Therefore, as an alternative to using actual mass degraded as suggested above, it is the author's opinion that prediction of gas production by the lambda method as modified by Lifrieri (2010) is most suitable for estimation of gas production, to determine percent biodegraded, and to determine time to end of biodegradation.

6.2 Development of Settlement Model Using Analyses of Biodegradable Mass

In order to assess the settlement of a landfill, the percentage change of volume with respect to time must be obtained. This percent volume change can be computed based on gas collection measurements. From the percent volume change, the percent strain (settlement) as well as percent biodegradation can be estimated. Since the areal extent of the landfill is quite large compared to its thickness, the volumetric strain can be approximated to be equal to the vertical strain of the landfill (its thickness). Two methods are presented herein to predict the settlement characteristics due to biodegradation. The first method is based on estimating percent degradation directly from loss of weight of degradable substances and/or gas production, whereas the second method is based on estimating biodegradation from field measurements of strain (settlement). The development of the model for both methods one and two will presented based on data from the composite sample only.

6.2.1 Method One – Mass Basis

The first method can be used for a scenario where a destructive sample of landfill waste can be obtained at multiple depths of the landfill thickness, or gas flow records are available. Although this destructive sampling is generally costly and involved, the author is aware of several landfills where destructive sampling is being carried out on regular intervals (Yazdani et. al 2006).

In the first method, plots for percent volume change with respect to time, percent biodegradation with respect to time, and percent strain with respect to time will be developed. The procedure for such method is presented here. To determine the magnitude of biodegradation of a given layer, the use of the biodegradation ratio, B, is introduced. The Biodegradation Ratio "B" at any time may be expressed as the total decomposed weight normalized by the weight of initial degradable weight, and as presented as Equation 6.10.

$$B_{mass} = \frac{\partial W}{(W_{tot} - W_{inert})} = \frac{\partial W}{W_{tot}(1 - R)} \tag{6.10}$$

The variable ∂W indicates loss of weight of degradable substance and is a function of time. Variable W_i is the initial total waste of the sample, while W_{inert} is the weight of the inert portion of the sample. The initial degradable weight of the waste sample can be determined by landfill and waste stream records of the placed waste. The loss of weight, ∂W, at any time can be obtained directly if a destructive sample can be taken. The author recommends determining the portion of total decomposed weight of the exhumed sample through loss on ignition.

In the expression presented as Equation 6.10, the inert waste divided by the degradable waste is expressed as inert weight ratio, R, and as defined in Equation 6.11. The ratio R can be obtained knowing the initial waste composition and percent inert matter of the composite waste. A value of 0.19 (19 percent) for R is evaluated for the work conducted herein based on the composite waste profile.

$$R = \frac{W_{inert}}{W_i} \qquad (6.11)$$

6.2.2 Method One – Volume Basis

The Equations 6.10 and 6.11 are based on defining biodegradation from loss of weight. However, biodegradation can also be computed based on volume measurements. To obtain a plot of percent biodegradation versus time for volume, the total theoretical gas potential must be determined. This is discussed in Chapter 3. The percent biodegradation at any time can be obtained by taking the cumulative volume of gas produced divided by the theoretical maximum at that given time. This is expressed as Equation 6.12. From this information, a plot of percent biodegradation versus time can be developed. The terms $V_{cumulative}$ and $V_{theoretical}$ indicate cumulative volume of gas collected up to time of interest and total theoretical gas potential, respectively.

$$\%B_{volume} = \left(\frac{V_{cumulative}}{V_{theoretical}}\right) \times 100\% \qquad (6.12)$$

A plot of percent biodegradation by mass compared to percent biodegradation by volume versus time is presented as Figure 6.16. This graph will be further discussed in Chapter 7.

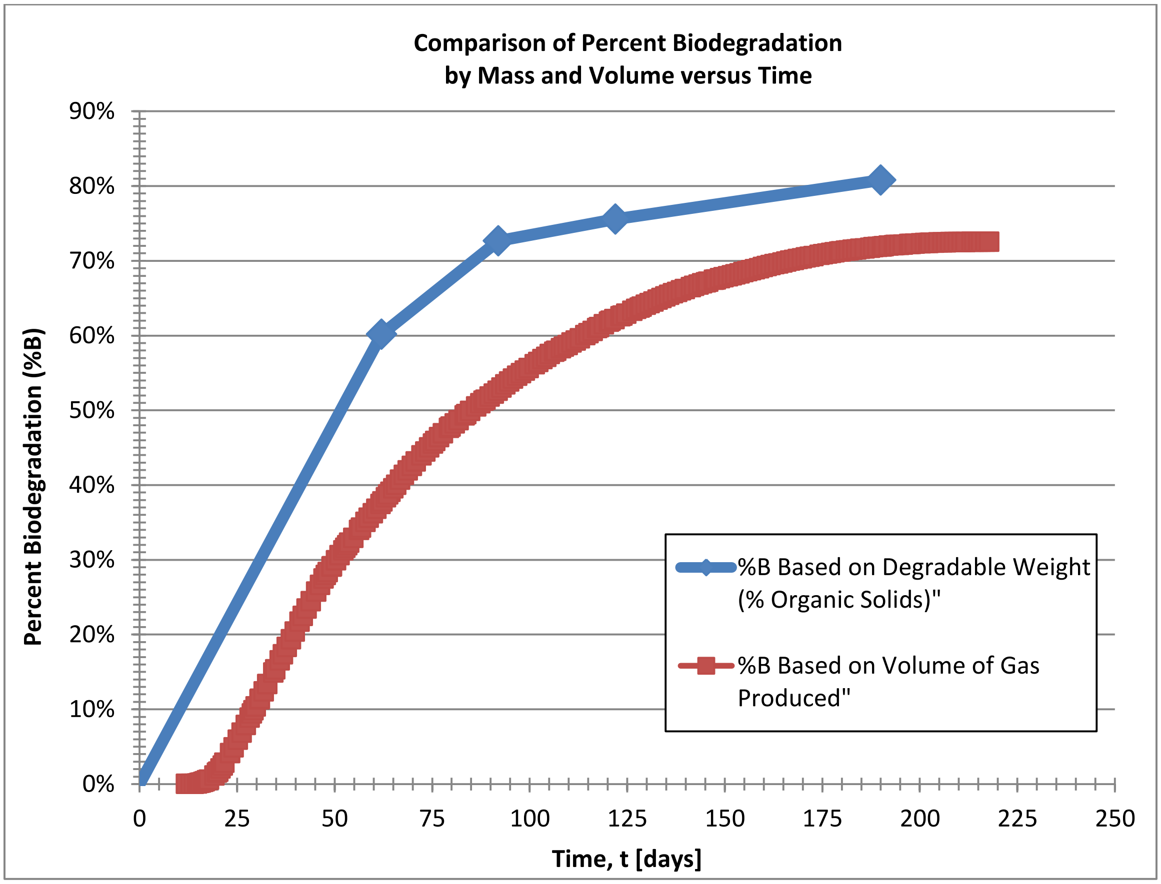

Figure 6.16 Comparison of Percent Biodegradation by Mass and Volume

For the computation using mass, by dividing the numerator and denominator of the expression provided as Equation 6.10 by area and unit weight, a relationship can be developed to determine the change in height at any time of the layer based on the biodegradation ratio at that time and original layer height. This expression is defined as Equation 6.13. For volume, percent biodegradation can be taken directly as expressed in Equation 6.12.

$$B = \frac{\partial h}{h(1-R)} \tag{6.13}$$

The biodegradation ratio alone is not directly related to vertical strain, and should not be taken synonymously as vertical strain. By calculating the change in height of the layer as indicated above, the vertical strain can then be determined by Equation 6.14. Derivation of the equation is provided in Appendix F – Derivation of Equations.

$$\varepsilon_z = B(1-R) \tag{6.14}$$

For this work, the percent biodegradation is computed using the volume relationship and gas collection data. This is based on the premise that the percent biodegradation due to volume is equal to percent biodegradation due to weight. More discussion regarding the applicability and limitations of this assumption are discussed in Chapter 7.

In order to create a unit-less ratio for field data comparison, time has been normalized to t_{50} which is the half-life of degradable components of the MSW. This is similar to the concept used by Durmesoglu et. al (2003), Findikakis and Leckie (1979), and the premise of first-order decay.

The author suggests generation of the following series of curves for the composite bioreactors to relate the gas production, the biodegradation ratio, and strain:

- Cumulative Total Gas Collected [ft^3/lb waste] versus Time, t
  (Figure 6.17)
- Loss of Biodegradable Weight [lb] versus Time, t
  (Figure 6.18)
- Biodegradation Ratio, B, versus Time, t
  (Figure 6.19)
- Biodegradation Ratio, B, versus Normalized Time, t/t_{50}
  (Figure 6.20)
- Strain, ε_z, versus Normalized Time, t/t_{50}
  (Figure 6.21)
- Percent Biodegradation Remaining [%] versus Normalized Time, t/t_{50}
  (Figure 6.22)

Table 6.5 has been provided to list the input data and sources used to generate the curves for the composite waste tested.

Table 6.5 Data Utilized to Correlate Gas Production to Biodegradation Ratio and Strain for Composite Bioreactors

Column Number							
1	2	3	4	5	6	7	8
Time Since Start, t [days]	**% Gas Collected Based on Theoretical Potential**	**Cumulative Weight of Decomposed Mass [lb]**	**Biodegradation Ratio, B**	**Normalized t/t_{50}**	**ε_z**	**Percent Biodegradation Remaining**	**Degradable Mass Remaining [lb]**
9	0%	0.000	0%	0.138	0.00	100%	1.70
14	1%	0.019	1%	0.215	0.01	99%	1.68
17	2%	0.038	2%	0.262	0.02	98%	1.66
19	3%	0.056	3%	0.292	0.03	97%	1.64
20	4%	0.075	4%	0.308	0.04	96%	1.62
21	6%	0.096	6%	0.323	0.05	94%	1.60
22	7%	0.115	7%	0.338	0.05	93%	1.58
23	8%	0.129	8%	0.354	0.06	92%	1.57
24	8%	0.143	8%	0.369	0.07	92%	1.55
25	10%	0.162	10%	0.385	0.08	90%	1.54
26	11%	0.180	11%	0.400	0.09	89%	1.52
27	12%	0.199	12%	0.415	0.09	88%	1.50
28	13%	0.220	13%	0.431	0.10	87%	1.48
29	14%	0.239	14%	0.446	0.11	86%	1.46
30	16%	0.276	16%	0.462	0.13	84%	1.42
65	50%	0.848	50%	1.000	0.40	50%	0.85
... ↓	... ↓	... ↓	... ↓	... ↓	... ↓	... ↓	... ↓
1056	95%	1.612	95%	1.00	0.77	5%	0.08
Note: Select data shown to represent example calculations used for graph data source							
DATA USED FOR CALCULATIONS							
W_i = 2.1 lb	W_{inert} = 0.4 lb	R = (W_{inert}/W_i) = 0.19	t_{50} = 65 days				
Formulas used:							
Column 1 = From total gas collection data collected by experiment							
Column 2 = From total gas collection data collected by experiment							
Column 3 = Column 2 x (W_i-W_{inert})							
Column 4 = Column 3 / (W_i x [1-R])							
Column 5 = Column 1 / t_{50}							
Column 6 = Column 4 x (1-R)							
Column 7 = (1 - Column 4) x 100%							
Column 8 = (W_i – W_{inert}) – Column 3							

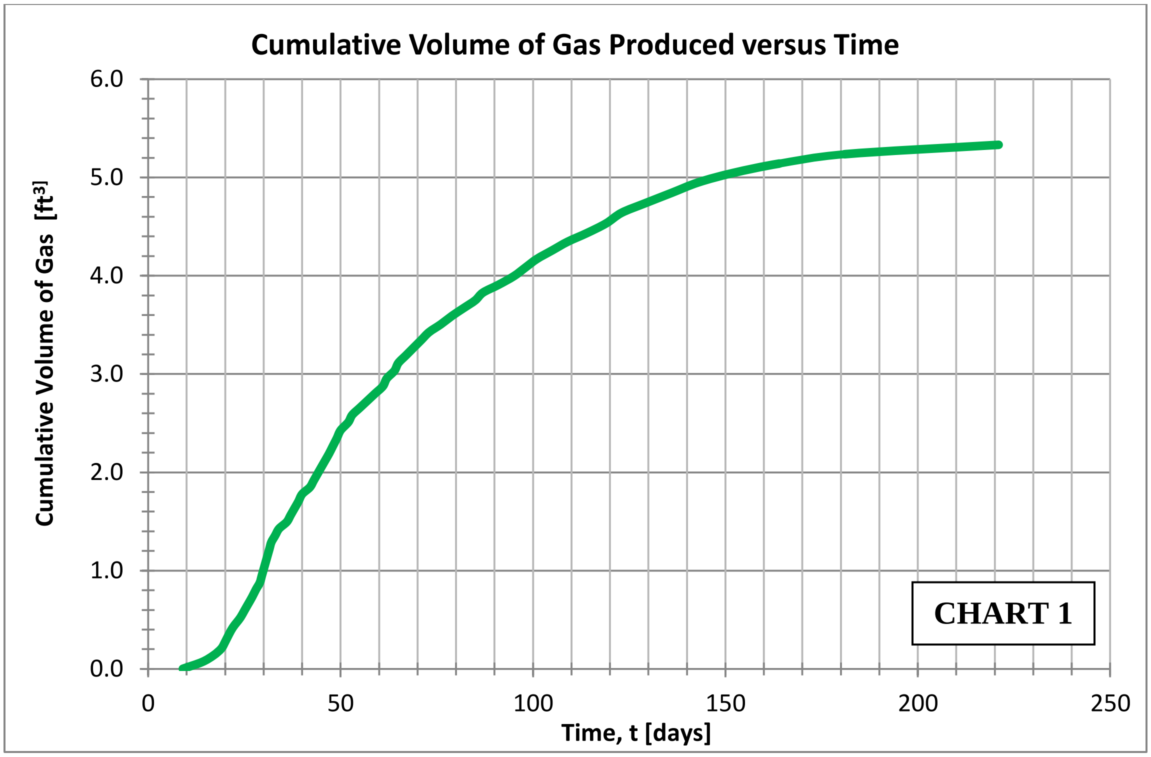

Figure 6.17 Cumulative Total Gas Collected [ft^3/lb waste] versus Time, t

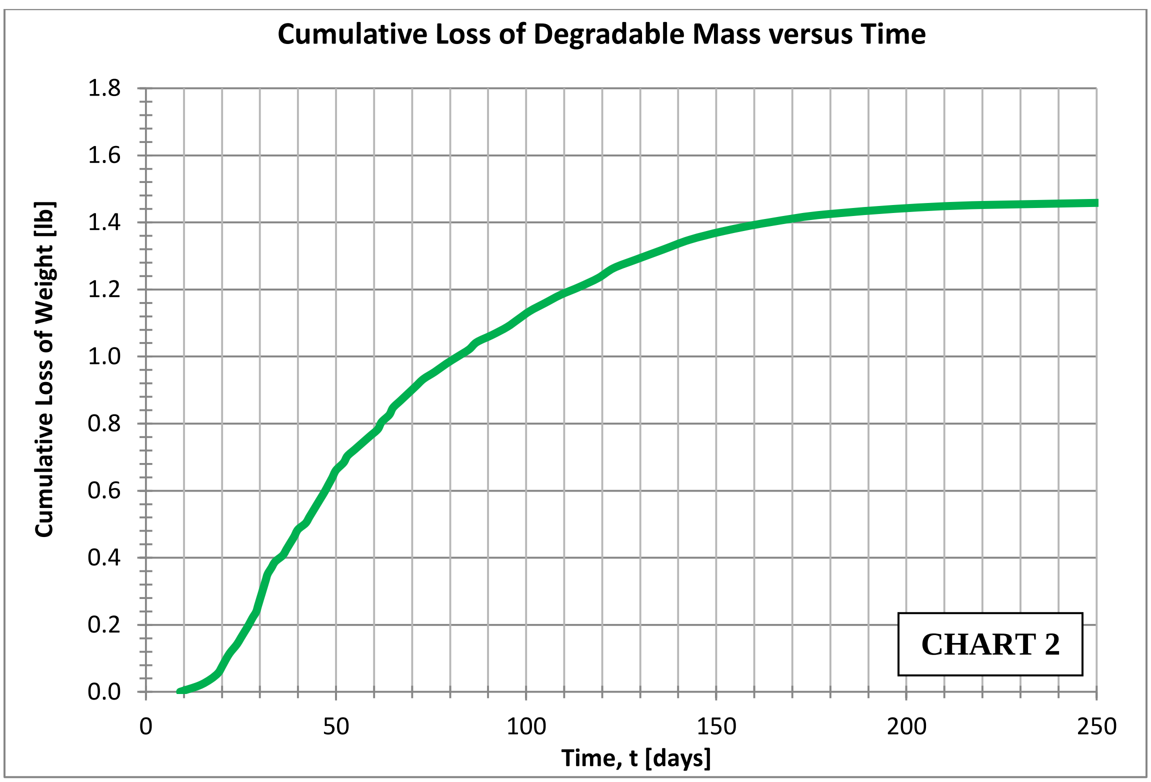

Figure 6.18 Loss of Biodegradable Weight [lb] versus Time, t

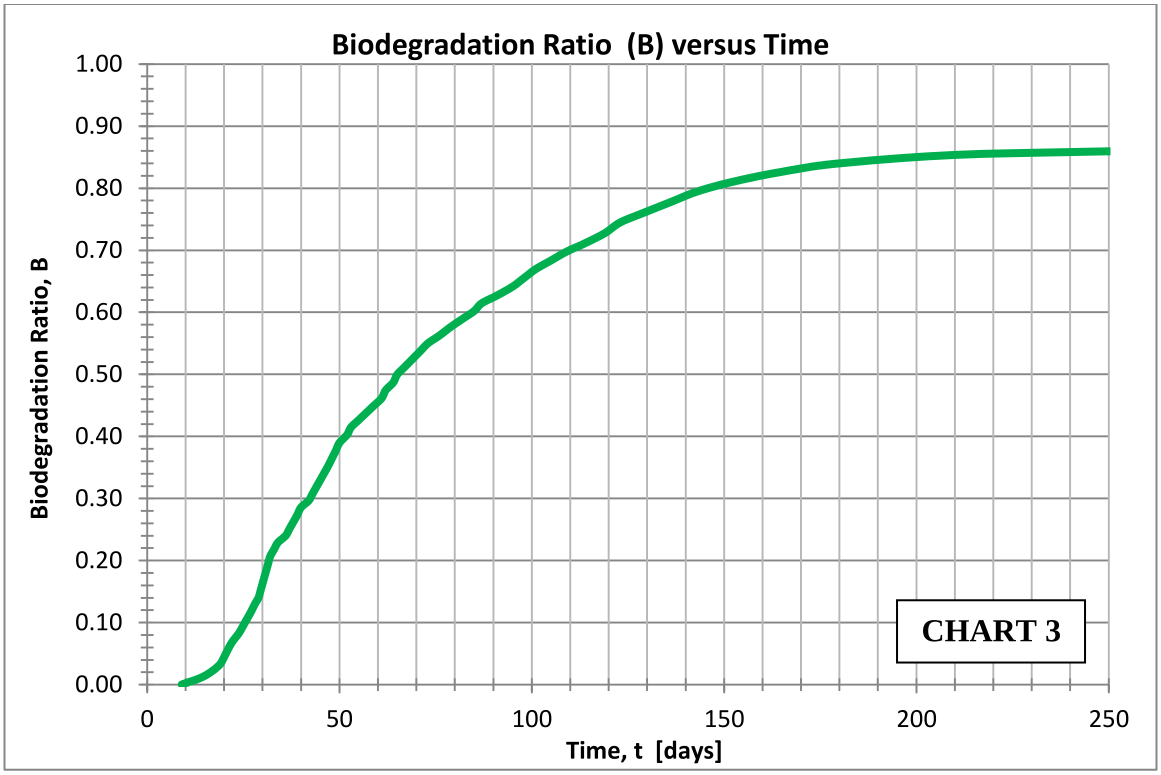

Figure 6.19 Biodegradation Ratio, B, versus Time, t

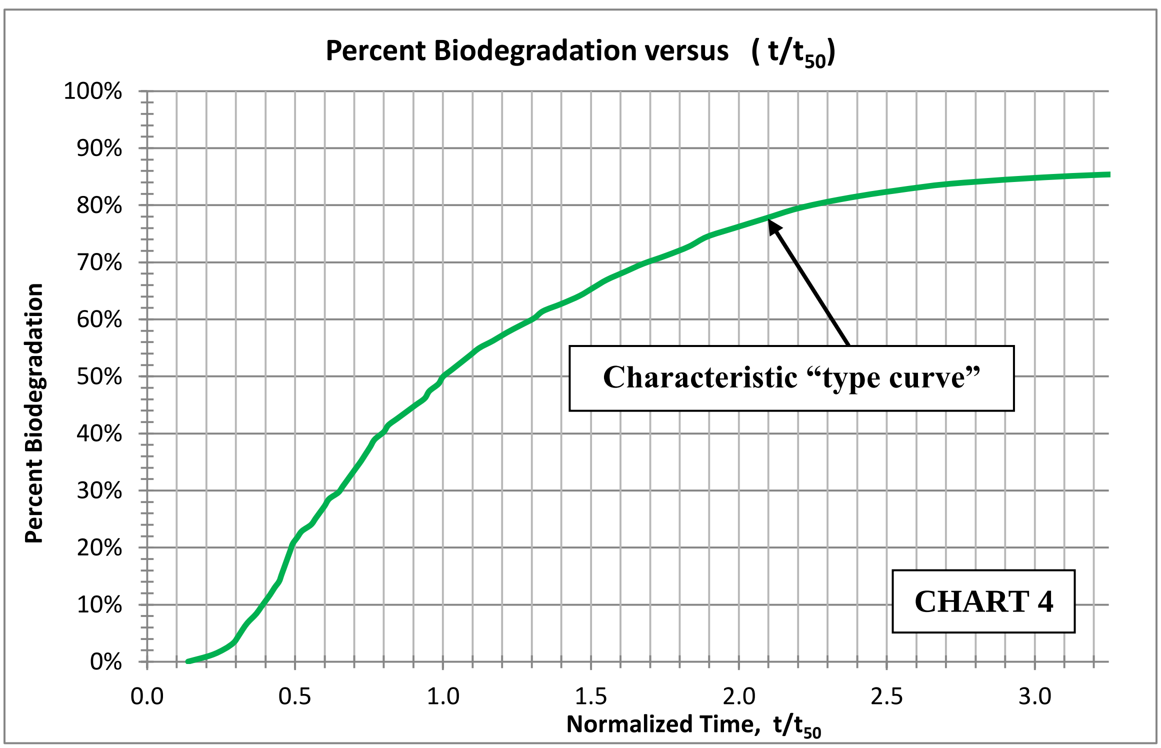

Figure 6.20 Biodegradation Ratio, B, versus Normalized Time, t/t_{50}

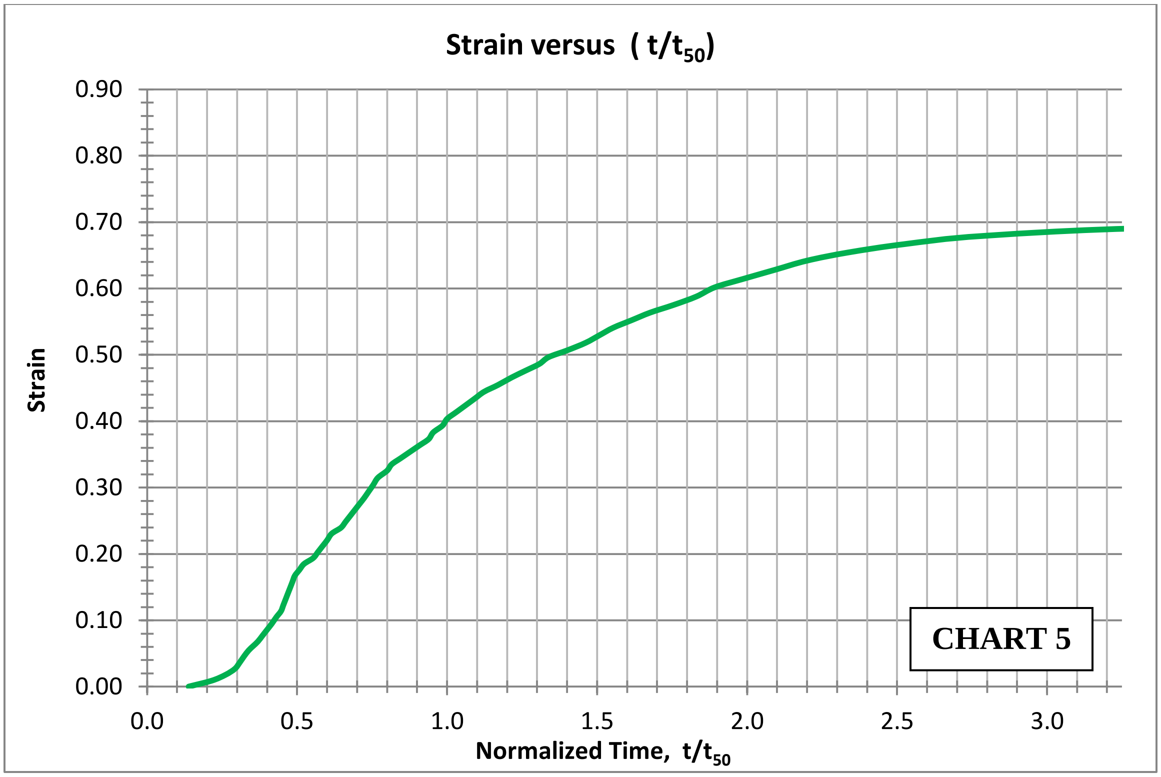

Figure 6.21 Strain, ε_z, versus Normalized Time, t/t_{50}

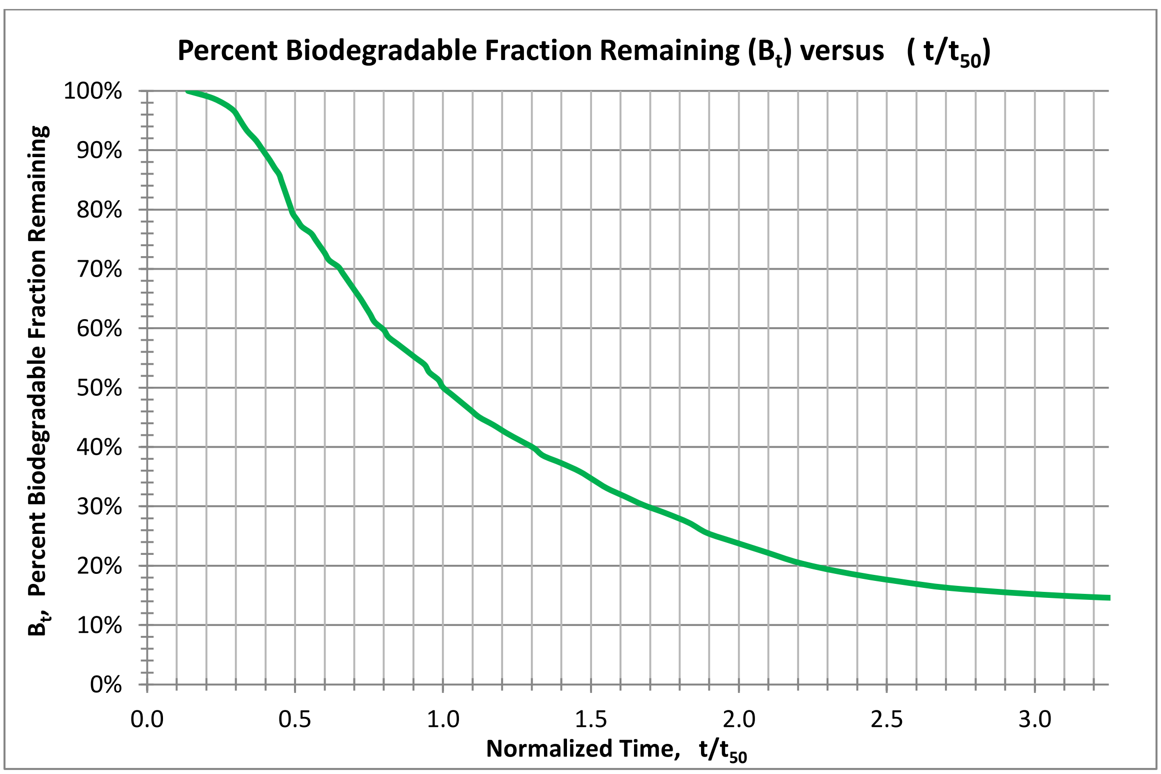

Figure 6.22 Percent Biodegradation Remaining [%] versus Normalized Time, t/t_{50}

The above process can be repeated and a settlement for each layer determined. The overall settlement as a result of mass degradation at any time may then be predicted by the addition of all the individual layer settlements. If the properties of a waste with a composition different from that tested for this study are required, the procedure in Table 6.6 may be used.

Table 6.6 Procedure to Obtain Characteristic Curve of Any MSW Composition

Step	Action
1	Determine the rate of gas production (*dy/dt*) versus time plot for the composition of the given MSW from the corresponding plots of readily and moderately degradable wastes using weighted averaging.
2	Determine the volume of gas produced (y) versus time plot for the composition of the given MSW by integrating the plot obtained from step 1 above.
3	Determine the theoretical maximum volume of gas collected using the modified Lambda method.
4	Using the graph created from Step 2, determine t_{50} , the time when 50% of theoretical gas is collected.
5	Determine the strain versus time plot for the given composite MSW. Also obtain the corresponding plot between percent volume change versus normalized time plot for the given composite MSW. The plot of strain versus normalized time should be used for analyses.
6	Determine the plot between percent biodegradation (based on volume) versus time plot for the given composite MSW. Also obtain the plot between percent volume change versus normalized t/t_{50} for the given composite MSW. The plot of percent biodegradation versus normalized time should be used for analyses.

The procedure above has been used to validate settlement of the Yolo County landfill evaluated in Chapter 7.

6.2.3 Laboratory to Field Scaling of Biodegradation and Settlement for Method One

The author comments that all of the previous modeling and information presented so far on biodegradation has been provided for laboratory conditions for one layer only. In the field, there are several layers of waste placed at different time intervals. Each layer will have its own separate state of biodegradation and settlement characteristics. For a landfill with *n* layers, an average biodegradation for the field condition can be computed as expressed in Equation 6.15 and 6.16.

$$B_{avg} = \frac{1}{h_{tot}} \sum_{i=1}^{n} B_i h_i \tag{6.15}$$

$$h_{tot} = \sum_{i=1}^{n} h_i \tag{6.16}$$

If the percent biodegradation for one layer is known, the author has provided the procedure to obtain biodegradation for several layers as shown as Figure 6.23. If the percent strain for one layer is known, a similar approach can be used to determine the strain of other layers. For this procedure the sequence of filling, thickness of each lift, and the time between placing each lift must be known. This is normally available from landfill records. The procedure is outline as Table 6.7.

Table 6.7 Procedure to Obtain Average Percent Biodegradation and Strain Based on Individual Layers

Step	**Action**
1	Obtain sample from layer 1 and determine B_1
2	Using Chart 4, locate point A for associated B_1
3	Using the time between lifts, $t_{ab,}$ normalize with $t_{50\ to}$ calculate T_{ab} and T_2
4	Using Percent Biodegradation (Chart 4), determine B_2 at normalized T_2/t_{50}
5	Repeat procedure for other lifts to establish percent biodegradation (B) for each layer
6	Determine average percent biodegradation (B_{avg}) for the entire landfill using Equation 6.15
7	Once B_{avg} is determined, average strain (settlement) can be obtained by Equation 6.14
Calculating average strain based on one known strain	
8	Using Chart 5, determine associated point A and Strain, ε_1
9	Determine settlement for layer 1 using initial layer thickness, H_1, and ε_1
10	Repeat above steps 1-4 for additional layers
11	Sum all individual settlements for total settlement at landfill at any given time
12	Percent strain can be determined by total settlement divided by landfill thickness
Note:	This procedure for a landfill with each layer having similar composition

The practical application of this model is to predict the settlement and biodegradation characteristics of a new landfill with several layers, and integrating this information into the design of the proposed landfill for planning. It can also be used to predict vital information such as time to substantial biodegradation and closure period. This model can also be used to predict the existing state of biodegradation of any landfill in operation. It can also predict subsequent biodegradation and strain (settlement) provided landfill records and waste composition are known. This technique along with the first method of the model is used to perform the field validation of settlement of the two selected landfills in Chapter 7.

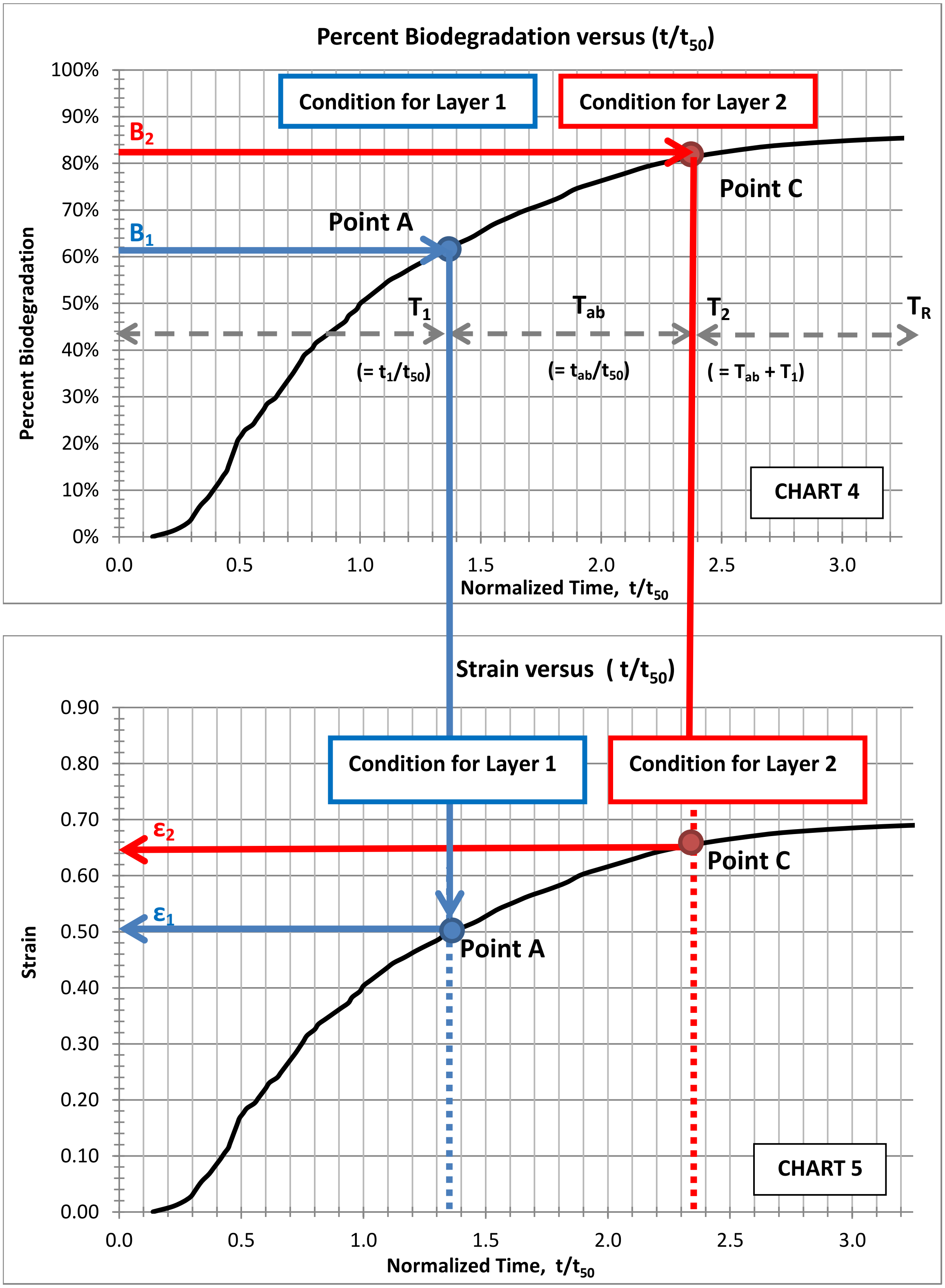

Figure 6.23 Example Procedure to Determine Average Percent Biodegradation and Based on One Known Sample Data Point

6.2.4 Method Two – Field Basis

The second method for analysis is suggested by the author to be used under a scenario when gas generation data and a destructive sample of landfill waste cannot be obtained. In this scenario, an average percent biodegradation will be established for the entire thickness of the landfill from the settlement data. Using the topographic data and using the strain at least four discrete time intervals, the field half-life constant can be calculated. This constant can be determined as the slope of a best-fit straight line between the natural log of strain versus time for the data set. The author derived the expression shown as Equation 6.17 to determine the field half-life coefficient knowing the strain between two time intervals. Derivation of the equation is provided in Appendix F – Derivation of Equations. In the expression, ε_{z1} and ε_{z2} are the average strain (%) for the year of interest and t_1 and t_2, respectively.

$$\lambda_{field} = \frac{\log_e(1-\varepsilon_{z_1}) - \log_e(1-\varepsilon_{z_2})}{t_2 - t_1} \qquad (6.17)$$

By knowing the field half-life constant, a plot of strain with respect to time can be established. Likewise, the half-life constant can be used to find t_{50}. Therefore, a strain versus normalized time ratio plot can be established using this half-life constant. An average percent biodegradation plot can subsequently be established by the known relationship between B and strain as discussed earlier.

It is the author's experience that exhuming of waste in a landfill may be regulated in certain locations, thereby requiring stringent permits for landfill disruption, specific requirements for excavation of waste, and financial implications to advance the process. While the author suggests destructive sampling and testing as in method one is the best method to determine actual characteristics of individual waste layers, it is recognized that landfill owners and operators may prefer a non-destructive sampling approach.

It is suggested to use historic topographic surveys of the landfill and waste placement records to aid in the prediction of settlement through this model. The settlement can then be determined by taking the difference between the topographic surveys at the end and start of the evaluation, and subtracting the thickness of additional waste placed since the start of the evaluation. The thickness of additional waste placed can be determined from landfill records. At least four years of topographic survey data are required for comparison.

For this study, method one is preferred as substantial data is available to support its use. Method two is provided as an approximation for preliminary analysis for landfill owners and operators.

6.3 Discussion of Consolidation Test Results and Settlement Model

From consolidation test readings, at termination of the experiment, 53 percent strain is observed as shown in Figure 5.17. Predicted strain due to mass decomposition indicates 68 percent strain as shown in Figure 6.21. The discrepancy may be due to soil arching, localized pockets of inert material, and size effects and overall heterogeneity of the waste.

Based on the characteristic curve provided as Figure 6.21, for a strain of 53 percent, the percent biodegradation is estimated to be 80 percent using Figure 6.20. This validates that the deformation is not complete, and that additional strain is expected. This is likely to be attributed to the presence of plastics, which require a much longer time for degradation. The author believes that the maximum strain expected to occur will be 68 percent based on mass lost. Additional discussion on the consolidation data is beyond the modified scope of this work as discussed in Chapter 5.

CHAPTER 7

VALIDATION OF MODEL

7.1 Validation of Model on Actual Landfill Data

This section discusses the validation of the model and the mass-degradation relationship proposed in Chapter 6. Two validation cases have been reviewed, one for a bioreactor landfill located in Cape May County, New Jersey and one for a bioreactor located in Yolo County, California. The cases were chosen to provide one landfill (Cape May County) with waste composition similar to the representative waste composition used for this experiment, and with comparable temporal, climatic, and regional variations for the waste constituents and landfill environment. The second (Yolo County) landfill allowed the author to draw a comparison for a differing waste composition and a substantially different climatic environment.

7.2 Model Validation on Cape May County Bioreactor Landfill

7.2.1 Description of Cape May County Bioreactor Landfill

The Cape May County Bioreactor Landfill, operated by the Cape May County Municipal Utilities Authority (CMCMUA) is located in the Borough of Woodbine, Cape May County, New Jersey. The landfill complex, which is situated on an approximately 478-acre parcel, accepts non-recyclable waste from all sixteen Cape May County municipalities.

The CMCMUA's MSW landfill complex consists of a double-lined landfill system with multiple cells. For the purposes of this work, attention is directed toward Cell 1E, one of three landfill cells located on 42 adjacent acres of area and which was designed and planned as a bioreactor landfill. The bioreactor design intended to inject leachate and optimize methane gas generation and collection to support waste-to-energy processes. The cell was lined and began accepting MSW waste in 2003. The cell stopped receiving waste in late 2007 after reaching capacity and was capped using a typical cap system (CMCMUA 2013).

7.2.2 Available Data from Cape May County Bioreactor Landfill

To support the use of the proposed model, it was anticipated that information regarding the waste composition, incoming tonnage records, and topographic data would be required, at minimum, for the cell. Tonnage reports, presented on an annual basis and separated by waste type, are provided in Appendix H – Field Validation Data and Calculations. Waste composition through tonnage records can be observed from these records. The composition for the CMCMUA Landfill E is generally in close agreement with the typical waste composition of Northeastern NJ as described in Chapter 4 and graphically in Figure 4.2, and as tested herein. Tonnage data is provided for all years of operation, including the 2003, 2004, 2005, 2006, and 2007 year.

As indicated in Chapter 6, it is recognized that landfill owners and operators may prefer a non-destructive sampling approach. Therefore, historic topographic surveys of the landfill were used to determine the thickness of waste at each location and settlement for subsequent years following closure.

A base grading plan from 2003 was obtained to determine the pre-fill elevation of the cell, along with a topographic survey conducted in 2007 immediately after waste placement ceased to represent the thickness of waste within the cell and top of waste elevation at closure. Data from aerial topography commissioned by CMCMUA for the 2012 and 2013 year was utilized to provide two independent data points representative of the waste at various stages of degradation following closure. Topographic surveys for each of the four years of interest are provided in Appendix H – Field Validation Data and Calculations.

7.2.3 Evaluation of Field Data

The author processed the topographic data by creating a grid system which could be overlaid above each topographic survey to determine the elevation at each grid point. Figure 7.1 depicts an example topographic survey with grid overlaid. Grid lines were spaced at 150 feet in each direction. Based on topography, points along grid line A and E represented sideslopes of the landfill. CMCMUA records indicated that spot filling frequently occurred on the sideslope along grid points A, which the author observed while comparing ground surface elevations between subsequent years. Grid points along "E" are adjacent to the currently-operational "Cell F", where CMCMUA indicated placement of waste occurs frequently along this sloped portion as it is adjacent to the active working face. Therefore, the points along grid lines A and E were not considered as representative for field validation presented herein.

For the purposes of validation, the author considered those points along grid lines B, C, and D as they are representative of the substantial mass of the landfill.

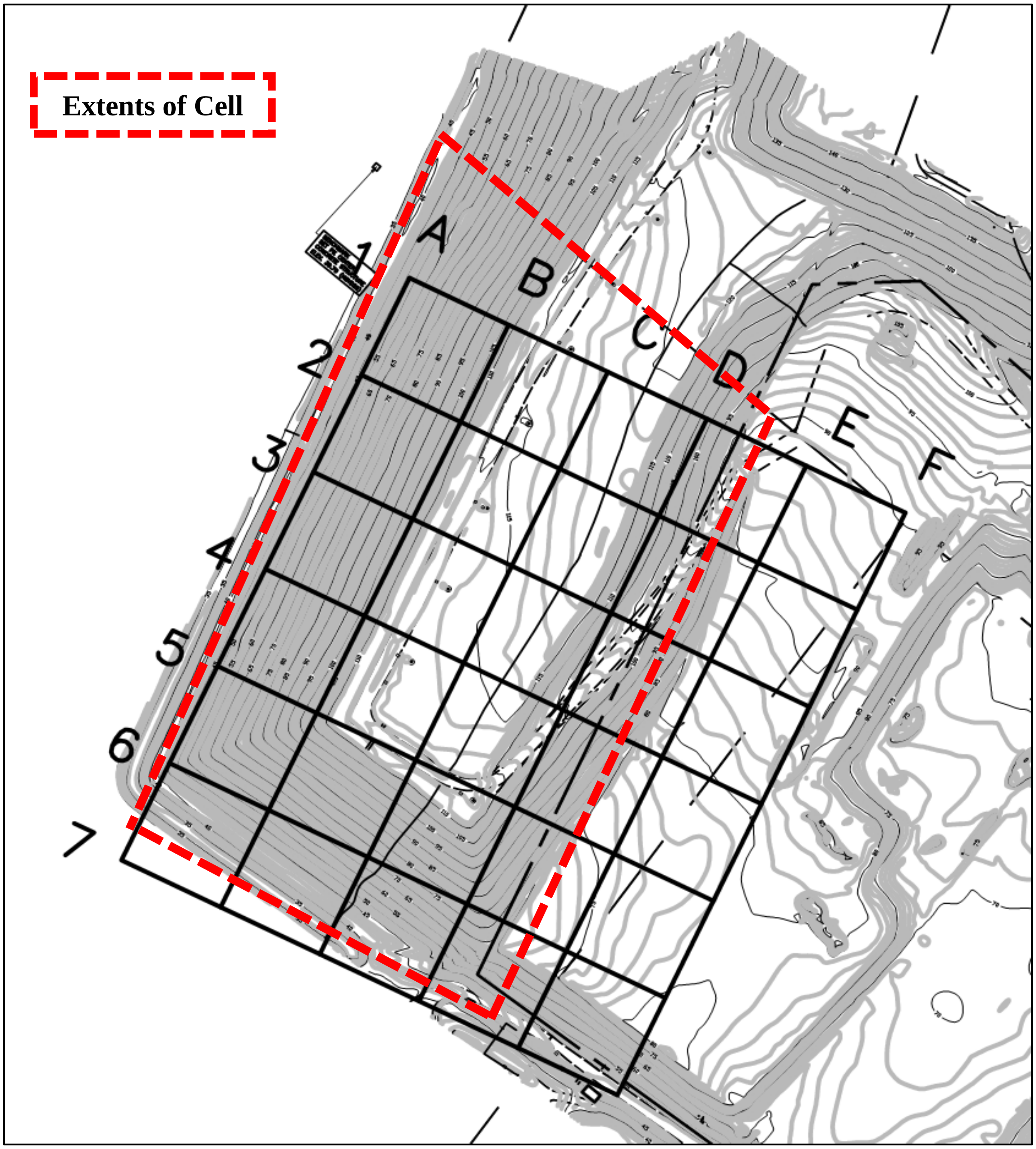

Figure 7.1 Example Topographic Survey (2012 Year) and Grid for CMCMUA Cell E

The author tabulated the ground surface elevation for the base elevation year (2003), closure year (2007), and two independent years (2012 and 2013) and provided the information as Table 7.1. The fill thickness at each grid point and settlement between closure year and each year of interest were subsequently calculated.

Table 7.1 Cape May County Topography and Determination of Ground-level Settlement

Grid Point	2003 Elev.	2007 Elev.	Fill Thickness [ft]	2012 Elev.	Settlement since Cap Year [ft]	% change from 2007 to 2012	2013 Elev.	Settlement since Cap Year [ft]	% change from 2007 to 2013	% change from 2012 to 2013
A1	32	55.52	23.52	51.1	4.42	19%	50.5	5.02	21%	3%
A2	33.7	53.02	19.32	51.2	1.82	9%	50	3.02	16%	6%
A3	32.2	51.4	19.2	50.1	1.3	7%	49	2.4	13%	6%
A4	34	50.32	16.32	50	0.32	2%	49.1	1.22	7%	6%
A5	35	48.44	13.44	46.4	2.04	15%	46.1	2.34	17%	2%
A6	35	44.12	9.12	44.6	-0.48	-5%	45	-0.88	-10%	-4%
B1	33.3	129.54	96.24	106.8	22.74	24%	105.6	23.94	25%	1%
B2	34.5	126.3	91.8	105.4	20.9	23%	103.8	22.5	25%	2%
B3	33.1	125.38	92.28	104.7	20.68	22%	103	22.38	24%	2%
B4	33.5	123.74	90.24	102.7	21.04	23%	101.4	22.34	25%	1%
B5	34.3	124.9	90.6	105.5	19.4	21%	103.8	21.1	23%	2%
B6	32.9	63.98	31.08	58.9	5.08	16%	58.6	5.38	17%	1%
C1	35	130.76	95.76	118.3	12.46	13%	116.1	14.66	15%	2%
C2	35.4	126.84	91.44	116.7	10.14	11%	114.6	12.24	13%	2%
C3	34.95	128.49	93.54	115.2	13.29	14%	112.9	15.59	17%	2%
C4	35	127.64	92.64	114.6	13.04	14%	112.3	15.34	17%	2%
C5	35.3	127.7	92.4	113.8	13.9	15%	111.3	16.4	18%	3%
C6	33.8	78.44	44.64	70	8.44	19%	69.1	9.34	21%	2%
D1	36.4	121.72	85.32	102.3	19.42	23%	102.3	19.42	23%	0%
D2	36.2	122.72	86.52	106.8	15.92	18%	104	18.72	22%	3%
D3	35.2	126.16	90.96	105	21.16	23%	103.3	22.86	25%	2%
D4	36.6	126.36	89.76	105.3	21.06	23%	103.5	22.86	25%	2%
D5	36.1	117.7	81.6	100.5	17.2	21%	98.4	19.3	24%	3%
D6	35.3	89.78	54.48	80.8	8.98	16%	79.6	10.18	19%	2%
Average of Grid Points along B									23%	
Average of Grid Points along C									17%	
Average of Grid Points along D									23%	
Average of B, C, and D									21%	

Since ground surface elevation and thickness of waste were known, strain observed over the time of interest can be calculated. The percent biodegradation can be obtained using Method One from Chapter 6. In Table 7.2, the author has provided calculations for average strain and percent biodegradation based on the field data.

Table 7.2 Calculation of Strain and Percent Biodegradation from CMCMUA Field Data

Calculation of Field-Observed Strain, ε_{zfield} :			
Average thickness of waste [ft] =	**90.74**	ft	(= average of waste thicknesses for all B, C, D grid points)
Avg $\varepsilon_{@start}$ =	0%		
Avg $\varepsilon_{@9\ yrs}$ =	19%		
Avg $\varepsilon_{@10\ yrs}$ =	**21.3%**		
Avg Annual ε =	2%		
Average Settlement, 2003 → 2012 [ft] =	17.54	ft	(= Avg $\varepsilon_{@9yr}$ x waste thickness)
Average Settlement, 2003 → 2013 [ft] =	19.36	ft	(= Avg $\varepsilon_{@10y}$ x waste thickness)
Average Annual Settlement [ft] =	1.82	ft	(= Avg Annual ε x thickness)
Calculation of Field-Observed Percent Biodegradation, %B_{field} :			
From Equation 6.13, $\varepsilon_z = B(1-R)$			
Therefore, Average %B = Avg ε/(1-R)			
Where R = % Inerts = 20% for this composition, so:			
Avg %$B_{@start}$ =	0%		
Avg %$B_{@9\ yrs}$ =	24%		
Avg %$B_{@10\ yrs}$ =	**26.7%**		
Average annual change in %B =	3%		

7.2.4 Computations Based on Model

The following analysis evaluates the theoretical strain and percent biodegradation of discrete layers using the procedure suggested as Method One in Chapter 6, and described as Figure 6.22 and Table 6.6. The analysis for this validation model is provided in Tables 7.3 and 7.4.

Table 7.3 Modeling of Landfill Layers and Lift Thicknesses

Example Cross Section:

Step 1: Determine landfill thickness, h_{tot} [ft]= 90.74

For this example, since we have waste composition and tonnage records on a yearly basis, split landfill layers up into one layer per year

Step 2: Number of years landfill in operation = 5
so, number of layers, "*n*" (1 per year) = 5

Step 3: Height of each layer [ft] = h_{tot}/n = 18.15

For this example, initial layer height, h_i [ft] = $h_{1i} = h_{2i} = h_{3i} = h_{4i} = h_{5i}$ = 18.15 ft

Step 4: Let t_0 = start of landfilling = 2003 year

Since we will be computing this analysis against topo for the 2013 year,
t_n = 2013 - (year waste placed)

(ex. t for 2003 year = 2013 - 2003 = 10
(10 years since waste placed)

Step 5*: For a bioreactor landfill, half-life constant "**λ**" = 0.07
(based on Barlaz, 2008, Hossain 2003 and originally as variable "k")
Therefore, time for 50% biodegradation, t_{50} [yr] = 9.90 = $-ln(0.5)/\lambda$
** See half-life discussion in Section 7.2.6.1*

Table 7.4 Computation of Theoretical Strain and Percent Biodegradation using Model

Step 6: Determine ε_z graphically by using the normalized graph of t/t_{50} and ε_z

(reference Figure 6.23 for example procedure)

Figure 7.2 provided for graphical determination of ε_z based on t/t_{50}

Step 7: Final layer height, h_f [ft] = $h_i - \varepsilon_z * h_i = h_i (1-\varepsilon_z)$

Step 8: %B = $\varepsilon_z / (1-R)$ *OR* obtained graphically from %B versus t/t_{50} graph
R = percent inert fraction of waste (= 20% for example composition = 0.2)

Figure 7.3 provided for graphical determination of %B based on t/t_{50}

Step 9: A table can be created to calculate t/t_{50}, ε_z, and %B, as shown below:

Layer	Year	Time, t [yr]	t/t_{50}	h_i [ft]	ε_z [%]	h_f [ft]	R	%B [%]
1	2003	10	1.1	18.15	40%	10.89	0.2	50%
2	2004	9	1.0	18.15	36%	11.61	0.2	45%
3	2005	8	0.9	18.15	32%	12.34	0.2	40%
4	2006	7	0.8	18.15	28%	13.07	0.2	35%
5	2007	6	0.7	18.15	22%	14.16	0.2	28%

Step 10: The average strain across each layer can be calculated as:
$\varepsilon_{zavg} = (\sum \varepsilon_z \text{ x } h_i)/\sum h_i$

So, ε_{zavg} = 32%

Step 11: The average %B across each layer can be calculated as:
$\%B_{avg} = (\sum \%B \text{ x } h_i)/\sum h_i$

So, $\%B_{avg}$ = 40%

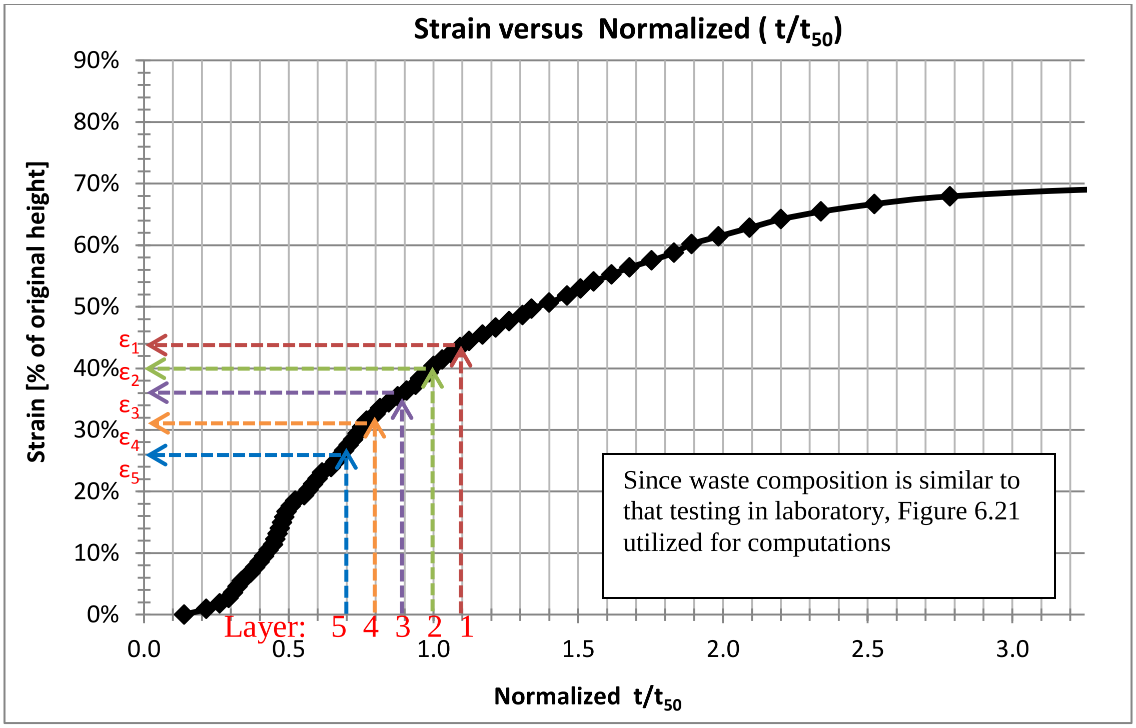

Figure 7.2 Graphical Determination of Strain, $\varepsilon_{z,}$ Based on Normalized t/t_{50} for Theoretical Calculation of CMCMUA Cell E

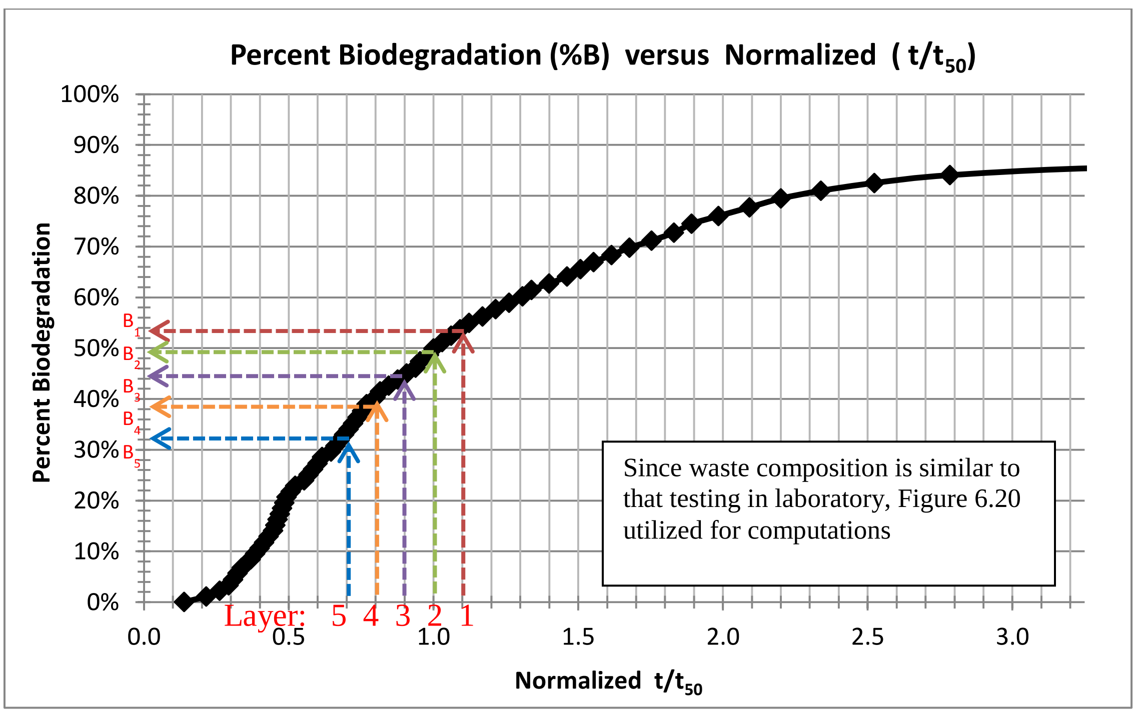

Figure 7.3 Graphical Determination of Percent Biodegradation, %B, Based on Normalized t/t_{50} for Theoretical Calculation of CMCMUA Cell E

From the graph above of percent biodegradation, it can be observed that the percent biodegradation versus time plot becomes nearly asymptotic after 85 percent. The probably explanation for this observation would be as follows: the proportion of the sum of the readily (31 percent of the degradable total) and moderately degradable fraction (53 percent of the degradable total) of the total biodegradable fraction is 84 percent. Hence, this indicates that the inclusion of the slowly degradable fraction is insignificant.

7.2.5 Discussion of Field and Model Data

From calculation of field data provided as Table 7.2, ε_{zfield} is determined to be approximately 21 percent, while ε_{zavg} from the model is 32 percent. Therefore, it appears that there is a difference of strain between between ε_{zavg} and ε_{zfield} of 11 percent on an overall average basis. Likewise, from Table 7.2, $\%B_{field}$ is approximately 27 percent and calculated $\%B_{avg}$ is 40 percent. Therefore, a variation of 13 percent is observed.

7.2.6 Factors Affecting Variation Between Field and Model Data

7.2.6.1 Waste Half-Life

Half-life will influence the normalized time ratio (t/t_{50}) used during the field validation process. To evaluate the effects of this, the author completed sensitivity analyses to determine the calculated strain and percent biodegradation based on three half-life constants. The analyses are summarized as Table 7.5. Rate constants used during the analyses were selected as discussed in Chapter 6 and as follows: one rate constant within the range recommended for wet landfills (0.07 $year^{-1}$); one rate constant equal to three times the average recommended traditional landfill rate constant (0.09 $year^{-1}$), and; one rate constant for the ideal bioreactor (0.12 year^{-1}) condition. The author recalls that the rate constant for wet landfills (0.07 year^{-1}) was utilized in the field validation model presented in Table 7.3 and 7.4 as the half-life of this rate constant is approximately 10 years and within the range supported by others.

Table 7.5 Sensitivity Analysis of Theoretical Strain and Percent Biodegradation for Differing Half-lives

	Half-life constant, λ [year^{-1}]		
	0.12	**0.09**	**0.07**
Half-life [yr]	**5.8**	**7.7**	**9.9**
$\varepsilon_{theoretical}$	49%	41%	32%
ε_{field}	21%	21%	21%
Difference	**28%**	**19%**	**10%**
$\%B_{theoretical}$	62%	51%	40%
$\%B_{field}$	27%	27%	27%
Difference	**35%**	**24%**	**13%**

From the analysis it can be observed that each additional increase of 0.01 year^{-1} to the decay constant will result in an additional 3 to 4 percent strain predicted by the theoretical model. Even though the ideal bioreactor rate constant of 0.12 year^{-1} is suggested by some researchers, it is the author's opinion that this value represents an ideal and optimistic scenario. Therefore, the use of this specific ideal constant value is not recommended. The remaining two rate constants indicate that the theoretical calculations for strain over-predict those observed from the field model by between 10 to 19 percent.

Using the topographic data presented in this study, the author calculated the field decay constant based on settlement, λ_{field}, to provide a comparison to theoretical constants. The above value was estimated to be 0.024 year^{-1} based on the data containing only two points as shown in Figure 7.4. It is to be noted that λ_{field} must be estimated from a Log ε_z versus time plot and with a number of data points collected over a long period of time.

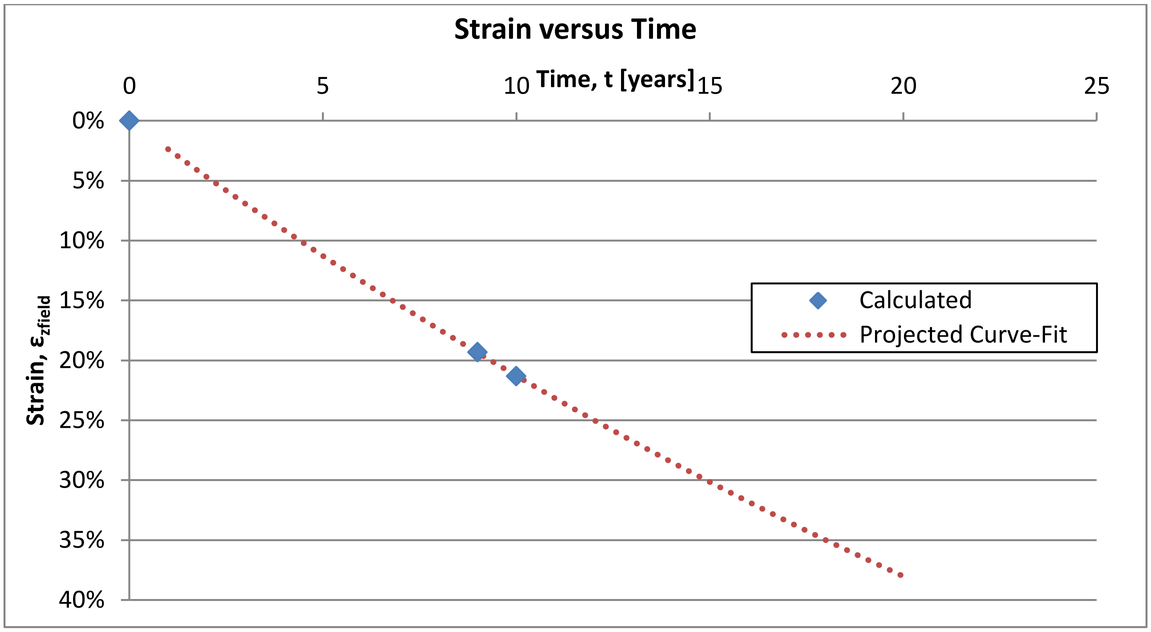

Figure 7.4 Projected Curve-Fit to Determine Field Half-Life Decay Constant for CMCMUA Cell E

It is to be noted that λ_{field} must be estimated from a Log ε_z versus time plot and with a number of data points collected over a long period of time. However, it was determined in Figure 7.4 using only two points representing data for only a short period of time. Hence the observed field half-life decay constant, λ_{field} (0.024 year^{-1}), is quite different from theoretical half-life decay constant, $\lambda_{theoretical}$ (0.07 year^{-1}). Consequently no conclusions can be drawn from λ_{field} and this value is not used for field validation purposes. The difference between half-life decay constants λ_{lab} (2.534 year^{-1}) and $\lambda_{theorectical}$, (0.07 year $^{-1}$) used for field validation may be attributed to several factors. These include those that may hinder the biodegradation process in field conditions and result in a lower field decay constant. One such factor is the availability of nutrients and mixture of leachate in a field-scale landfill. In a laboratory environment, leachate, moisture, and nutrients are well-mixed into the sample which allows for more mass to leachate and nutrient contact.

Comparatively, in a field environment there is less mass to leachate and nutrient contact. This may be attributed to the inability of leachate piping to reach all pockets of waste, shadowing effects from larger construction and demolition debris or large white goods, and inadequate conditions to support decomposition such as temperature variations, aerobic conditions, and hazardous substances which hinder microbe activity.

The author suggests another factor that may be attributed to the inherent circumstance that waste is placed in layers throughout the course of the filling process. This process would result in each layer existing at a different state of biodegradation, with the aged waste layers behaving differently than layers of fresh waste. For example, the fresh waste may exhibit one decay constant, however all remaining lifts may exhibit decay constants lower than the freshly placed layer and therefore produce a lower average decay constant.

The author comments that Barlaz et al. (2008) recognize the discrepancy between field and laboratory conditions and attempt to introduce a correction factor, f, to describe the variation between the two data sets. A standard range of values for the correction factor is not presented by the authors and it is ambiguous if a basis other than curve-fitting exists to determine the factor.

7.2.6.2 Waste Composition

From inspection of the topographic data provided in Table 7.1, it is noted that the average percent strain between grid points along B are nearly identical to those along line D. However, the average percent strain of grid points along line C are 6 percent lower than that of B and D. This may be attributed to a number of factors, such as variation in composition, presence of more inert matter, potentially large bulky items and debris, and presence of more slowly biodegradable matter. Additional discussions regarding the potential variations between field and model are discussed below.

Also, it is noted from discussions with CMCMUA that construction and demolition debris, including wood and concrete, was placed in the landfill periodically during several substantial storm events. Therefore, it is the opinion of the author that the inclusion of these wastes may have increased the slowly degradable and inert components of the waste composition. This may have extended the overall average half-life of the waste contained in the landfill, and increased the half-life up to the upper-bound for bioreactor landfills of 15 years as discussed in Chapter 5. Based on this, using the procedure outlined in Table 7.3 using a t_{50} of 15 years, the calculated theoretical strain is nearly 21 percent. This is very close to the field-observed average strain of also approximately 21 percent. Therefore, it is hypothesized that the inclusion of this debris may further restrict the circulation of leachate and hence the availability of nutrients to promote enhanced biodegradation as expected and increase the half-life of the waste.

7.2.6.3 Waste Density

Another reason to explain the difference of between 13 to 24 percent biodegradation between the field and model could be attributed to variations in waste density. To understand the influence of density, a parametric analysis was conducted to determine percent biodegradation based on both degradable weight loss (percent organic solids) and cumulative volume of gas collected with respect to time. Evaluation of percent biodegradation based on degradable weight loss and volume of gas are discussed in Chapter 6.

As discussed in Chapter 5 and summarized in Table 5.11, at the end of the experiment, decommissioning records showed the average final density of the composite waste sample was 91 percent of the average initial sample density. Rearranging the equations on degradable weight loss and volume of gas expressed in Chapter 6, the author derived Equation 7.1 to account for the variation due to density in addition to degradable weight loss. In the expression, the terms γ_i and γ_f indicate initial and final unit weight of the waste. Derivation of the equation is provided in Appendix F – Derivation of Equations.

$$\%B_{converted} = [1-(\frac{\gamma_i W_{final}}{\gamma_f W_{initial}})]\times 100\% \qquad (7.1)$$

The results of the parametric analyses are provided graphically as Figure 7.5. The author comments that the results indicate that up to a 10 percent variation could exist due to effects of density. However, the average of the biodegradation values based on mass and on mass with density effects produce a convergence close to that observed by volume. This density variation has been discussed further in Chapter 5.

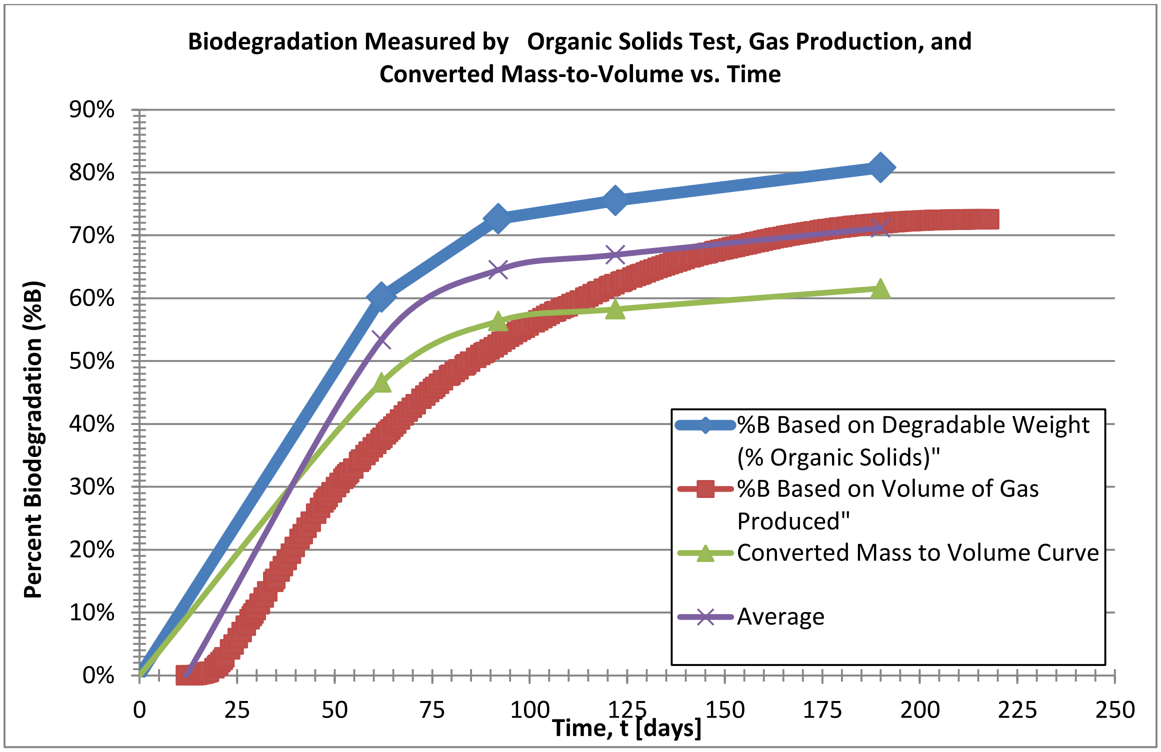

Figure 7.5 Parametric Analyses To Determine Variation Of Percent Biodegradation Due To Multiple Methods.

7.2.6.4 Bulky and Slowly Degradable Wastes

In addition to density effects, it is suggested that the presence of plastic may also contribute to the difference between calculated theoretical and field-observed results. It is commented that plastics make up 12 percent of the waste composition tested in this work. As the recycling rate increases, the author believes that the proportion of plastics in the waste will decrease. Because of this reduction, the degradable organic fraction will increase. This will cause a reduction in the percent biodegradation based on Equation 6.10.

The calculations provided as Table 7.6 were completed to understand the effect of removing plastics and effect on the half-life decay constant or half-life. It is determined that removing the plastics had little to no measurable effect on the calculated composite half-life constant (λ_c), determination of half-life (t_{50}), and end of decomposition (t_{95}).

Table 7.6 Effect of Removing Plastics on Composite Half-life Constant (λ_c), Determination of half-life (t_{50}), and End of Decomposition (t_{95})

Known Information:
From Table 6.2, half-life constants (λ_i) for each waste type are as follows: λ_r = 6.609 year^{-1} λ_m = 1.723 year^{-1} λ_s = 0.011 year^{-1}
Calculated Composite Half-life Constant – With Plastics:
Using the waste proportion considered for this experiment, the adjusted λ values (λ_i*) to create the λ_c are: λ_r* = 1.652 year^{-1} (= 6.609 x 25%) λ_m* = 0.741 year^{-1} (= 1.723 x 43%) λ_s* = 0.0013 year^{-1} (= 0.011 x 12%) Therefore, $\lambda_c = \lambda_r^* + \lambda_m^* + \lambda_s^*$ = 1.652+0.741+0.0013 = 2.39 year^{-1} Plastics make up 0.0013/2.39 = .000544 (or 0.05%) of the composite λ factor. Therefore, **plastics account for less than 1% of the composite half-life decay factor, λ_c**
Calculated Composite Half-life Constant – Without Plastics, Half-life (t_{50}), and End of Decomposition (t_{95}):
Let us next consider the effects of including and removing λ_s (plastics) in the composite λ and effect to laboratory-based half-life (t_{50}) and t_{95}. With plastics (λ_s) included, λ_c = 2.39 year^{-1} , and: t_{50} = -ln (0.5)/2.39 year^{-1} = 0.29 year = 105.85 days t_{95} = -ln(0.05)/2.39 year^{-1} = 1.25 year = 457.50 days With plastics (λ_s) removed, λ_c = 2.39 – 0.0013 = 2.3887 year^{-1} , and: t_{50} = -ln (0.5)/2.3887 year^{-1} = 0.29 year = 105.91 days t_{95} = -ln(0.05)/2.3887 year^{-1} = 1.25 year = 457.76 days
Conclusion:
Removing the plastics has little to no measurable effect on the calculated composite λ, determination of half-life (t_{50}), and end of decomposition (t_{95})

Also, as topographic data is used to measure field conditions, it is likely that the topographic data is skewed more towards measuring settlement of the underlying waste material as reflected at the surface. It does partially represent the settlement from lower layers; however, the settlement at the lower layers may not be reflected upward to the surface due to phenomenon such as soil bridging, burial of large waste/white goods (bulky wastes), and other size effects. This can effect can be greater in landfills with greater thickness of placed waste. Lifrieri (2010) observed this similar phenomenon in validations of his work on the Kingsland Landfill and Connecticut Site C landfill, where settlements between years increased drastically. As he suggested this may be attributable to the collapsing of voids, which are created through bridging and arching around bulky items such as the noted buried construction and demolition debris.

For the validation case on CMCMUA Cell E, the author summarizes that the percent biodegradation predicted by the theoretical method is 3 and 14 percent less than the observed field results once an estimated 10 percent variation due to density variations is removed.

It is noted earlier construction and demolition debris, including wood and concrete, was placed in the landfill periodically during several substantial storm events. Therefore it is suggested that inclusion of these wastes, which increases the slowly degradable and inert components of the waste composition, may have decreased leachate and nutrient availability. The effect of this would result in an overall average half-life of the waste contained in the landfill. It was shown that, by increasing the half-life up to the upper-bound for bioreactor landfills of 15 years, a closer fit is achieved.

The author comments that the remaining difference is within limits generally accepted by industry and practice for solid waste. The inherent heterogeneity of the material, waste characterization variations, landfilling processes, and climatologic differences will affect predictions for the behavior of MSW. Hence, some variation between observed and predicted values is expected.

7.3 Model Validation on Yolo County Bioreactor Landfill

7.3.1 Description of Yolo County Bioreactor Landfill

The Yolo County Department of Planning and Public Works constructed and currently operate a full-scale bioreactor landfill at the Yolo County Central Landfill near Davis, California since 2001. The work, which was supported by the Environmental Protection Agency's (EPA) Project XL program, was proposed to develop innovative approaches for carbon sequestration and greenhouse emission control. The objective of the project was to manage landfill solid waste for rapid waste decomposition and maximum landfill gas generation and capture for carbon sequestration and greenhouse emission control. The first phase of the project entailed the construction of a 12-acre module, containing a 3.5-acre anaerobic cell where leachate injection and circulation was conducted to simulate a bioreactor condition (Yazdani et. al, 2006). Performance data for the bioreactor landfill is made available through periodic published technical progress reports to fulfill United State Department of Energy grant requirements, and provide useful information to practitioners, legislatures, and environmental reviewers to support the adoption of the bioreactor landfill concept.

The author notes several similarities between the experimental work conducted herein, and the full-scale conditions of the field bioreactor landfill. Yazdani et. al (2006) indicate that, from the start of full-scale operations, elevated temperatures (about 110-140°F) were measured throughout the bulk waste in both cells. The cited work indicates that waste temperatures inside the cells remained constant and essentially independent of ambient temperature, and that these temperatures contributed to the acceleration of the microbial degradation of the waste and methane production. The author comments that this corroborates the similar temperature range used during the laboratory experiment to enhance mesophilic processes.

Likewise, typical standard of practice procedures were used to compact the waste within the field bioreactor landfill. Waste was placed in loose lifts not exceeding 24 inches with either a Caterpillar D-7 or D-8 dozer, and then was compacted with between 3 to 5 passes using a Caterpillar 826C sheeps-foot compactor. Initial density of the in-situ waste was measured to be approximately 36 pounds per cubic foot, which is generally similar to the target experimental density of 40 pounds per cubic foot used in the laboratory work for this study. Moisture content of the field bioreactor was continually monitored at selected points within the landfill using moisture probes and an automated SCADA control system. Additionally, the operational strategy of the landfill consisted of conducting leachate addition when moisture content decreased below 40 percent. In a similar regard, the experimental work conducted for this study performed leachate injection activities at an identical moisture content threshold. The author attempted to obtain details regarding the leachate circulation system, frequency, and procedure; however, these records are not currently made available.

7.3.2 Evaluation of Field Data

Data contained within the published technical progress reports provided landfill thickness and annual topographic data to support the determination of settlement for use of the model proposed herein. Waste composition was determined using regional waste characterization study data conducted by the California Integrated Waste Management Board (CIWMB, 2000). In table 7.7, waste composition for the considered region is summarized. Detailed categorization of each waste type and relevant excerpts for the cited waste characterization study is provided in Appendix H – Field Validation Data and Calculations.

Table 7.7 Characteristics of Yolo County, California Waste

Constituent	Descriptive Modifier	Percent of Waste
Food	Readily Degradable	15.7%
Grass and Trimmings	Readily Degradable	10.2%
Other Organics	Readily Degradable	7.0%
Paper	Moderately Degradable	30.2%
Lumber/Wood	Moderately Degradable	4.9%
Textiles	Moderately Degradable	2.1%
Plastic	Slowly Degradable	8.9%
Glass	Inert	2.8%
Metal	Inert	6.1%
Construction/Demolition Waste & Soil	Inert	6.7%
Household Hazardous Wastes/Oils	Inert	0.3%
Ash & White Goods/Bulky Items	Inert	3.1%
Mixed Residue	Inert	2.0%
	TOTAL:	***100.0%***
	% Readily Degradable	32.9%
	% Moderately Degradable	37.2%
	% Slowly Degradable	8.9%
	% Inert Waste	21.0%
		Source: California Integrated Waste Management Board (CIWMB, 2000)

Placement of waste began in the 3.5 acre bioreactor cell on January 13, 2001 and was completed on August 3, 2001. Landfill records indicate waste was placed in four separate lifts, each with an approximate thickness of between 7 to 15 feet. A cross section of the bioreactor is represented as Figure 7.6. Following completion of waste placement, final grading on the cell occurred in August and September of 2001. Final grading consisted of placement of a one foot thick layer of soil over the waste and a synthetic geomembrane cap (Yazdani et. al, 2006).

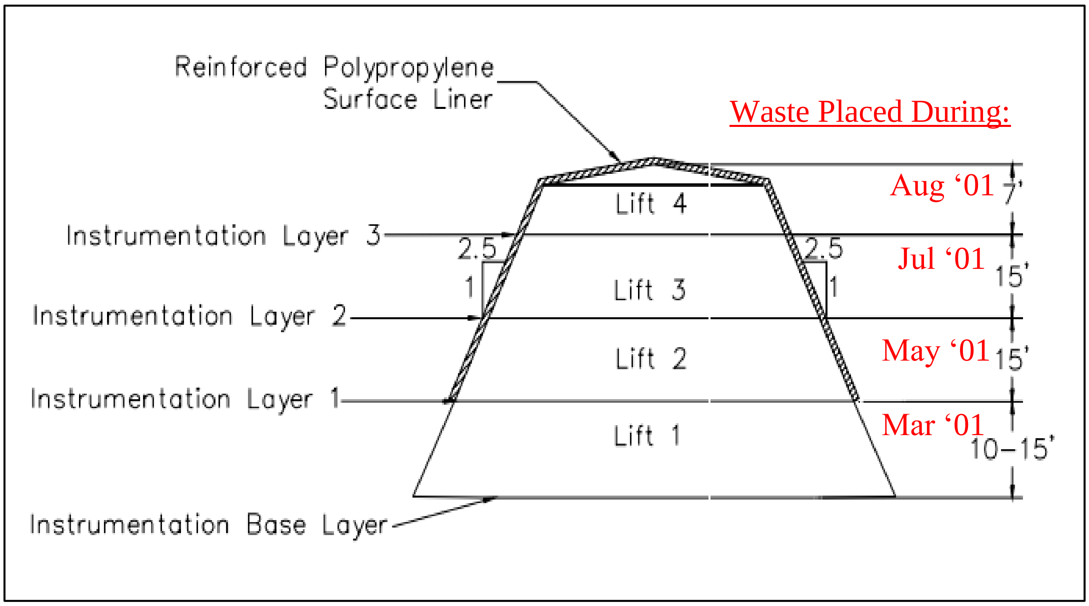

Figure 7.6 Schematic of Waste Placement in Yolo County Bioreactor Landfill Cell
Source: Yazdani et. al (2006)

Once closed, an initial topographic survey for the cell was performed on November 15, 2001. This baseline survey was used as the reference for calculating the total settlement of the cell. The second and third surveying events included in the technical progress report were completed on January 16, 2003, and January 28, 2004, respectively. The surveys presented topographic data with half-foot and one foot contours, respectively.

In addition to the topographic surveys, settlement was also calculated utilizing 22 separate control monuments established on the surface liner. Initial elevations of the survey monuments were taken during the initial topographic survey of each of the cells. The total depth of waste was subsequently calculated by comparison of the known elevation of the base liner and surface liner. Subsequent surveys then established the new benchmark elevation, and the percent settlement was calculated relative to the waste depth at each benchmark location. It is reported that the settlement from the benchmarks was within 5 percent of the topographic survey, and therefore convergence was achieved between the two methods. Settlement data supplied by Yazdani et. al (2003) for the Yolo County bioreactor landfill is provided as Figure 7.7.

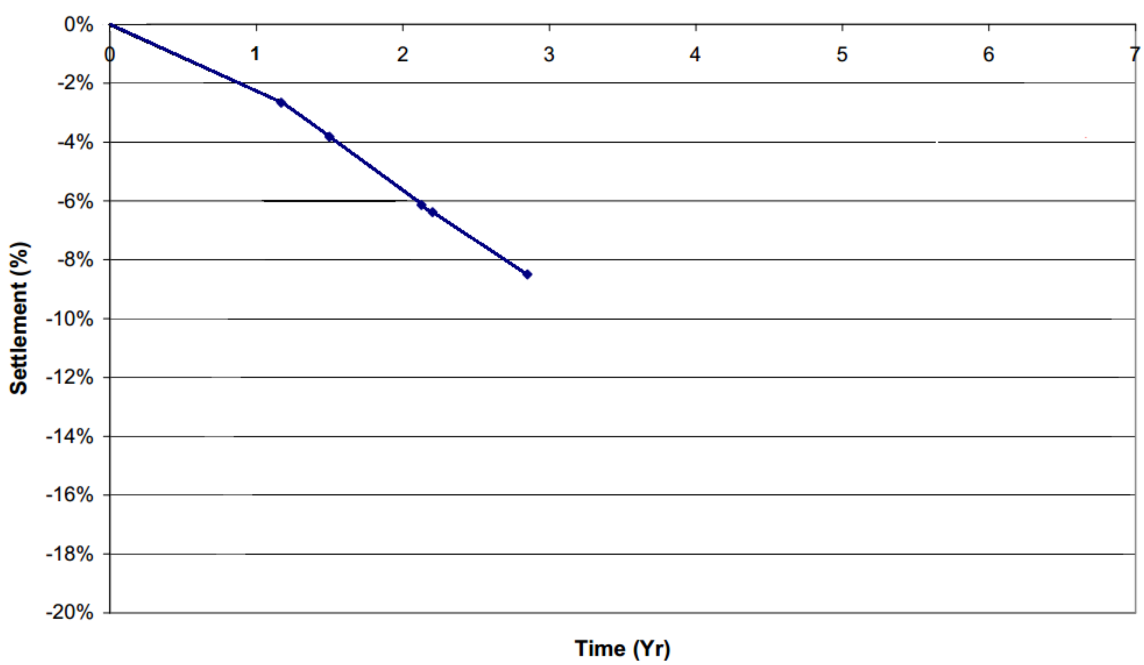

Figure 7.7 Settlement Versus Time Measured for Yolo County Bioreactor Landfill
Source: Yazdani et. al (2006)

As the settlement is provided as a function of the initial waste thickness, the strain observed over the time of interest is directly provided. The calculated field half-life decay constant (λ) is 0.031 year^{-1}. Actual average percent biodegradation could then be ascertained using the procedure similar to Table 7.2. The author has provided calculations for average strain and percent biodegradation based on field data for the Yolo County bioreactor landfill as Table 7.8.

Table 7.8 Calculation of Strain and Percent Biodegradation from Yolo County Bioreactor Landfill Field Data

Calculation of Field-Observed Strain, ε_{zfield} :			
Thickness of waste [ft] =	**49.5**	ft	= 12.5 feet (layer 1) + 15 feet (layer 2) + 15 feet (layer 3) + 7 feet (layer 4)
$\varepsilon_{@start}$ =	0%		
$\varepsilon_{@1\ yrs}$ =	3.9%		
$\varepsilon_{@2.5yrs}$ =	**8.3%**		
Avg Annual ε =	3.3%		
Settlement, Nov 2001 → May 2003 [ft] =	1.96	ft	(= Avg $\varepsilon_{@1yr}$ x waste thickness)
Settlement, Nov 2001 → Aug 2004[ft] =	4.10	ft	(= Avg $\varepsilon_{@2.5y}$ x waste thickness)
Average Annual Settlement [ft] =	1.41	ft	(= Avg Annual ε x thickness)
Calculation of Field-Observed Percent Biodegradation, %B_{field} :			
From Equation 6.13, $\varepsilon_z = B(1-R)$			
Therefore, Average %B = ε / (1-R)			
Where R = % Inerts = 21% for this composition, so:			
Avg %$B_{@start}$ =	0%		
Avg %$B_{@1\ yrs}$ =	5.0%		
Avg %$B_{@2.5yrs}$ =	**10.5%**		
Average annual change in %B =	4.2%		

7.3.3 Computations Based on Model

To support the use of the model for a MSW landfill with waste composition unlike that from New Jersey tested herein, a composite characteristic curve must be assembled. This is done using gas production curves of each of the three descriptive waste modifiers provided in Chapter 6. The procedure followed is as given in Table 6.6.

Following Step 1 of the procedure, a composite plot of gas production rate versus time has been assembled using proportions from the waste characterization outlined in Table 7.8. The plot is provided as Figure 7.8.

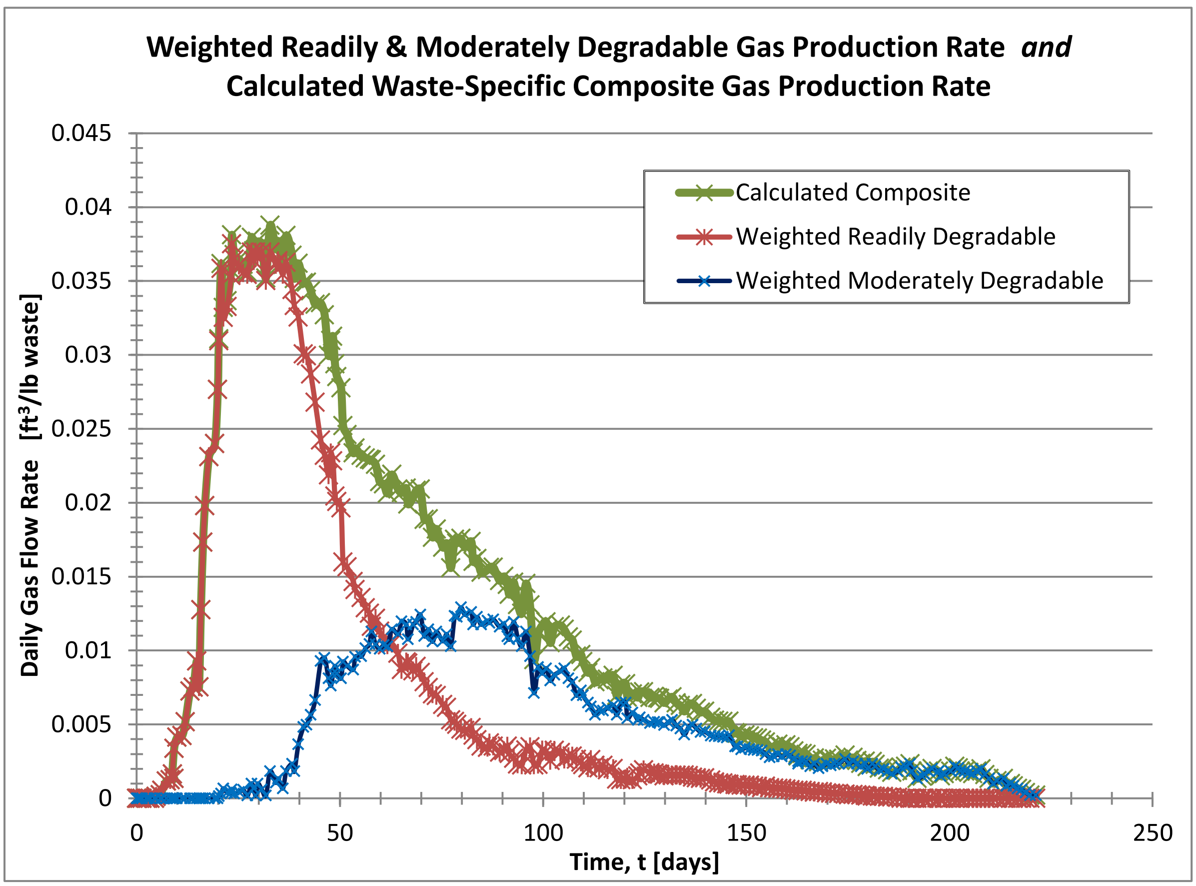

Figure 7.8 Weighted Readily and Moderately Degradable Gas Production Rate and Calculated Waste-Specific Composite Gas Production Rate versus Time

Based on Step 2 of the procedure, the plot of gas production rate versus time is integrated to create a plot of cumulative total gas production versus time for the specific waste characterization considered. The plot is provided as Figure 7.9.

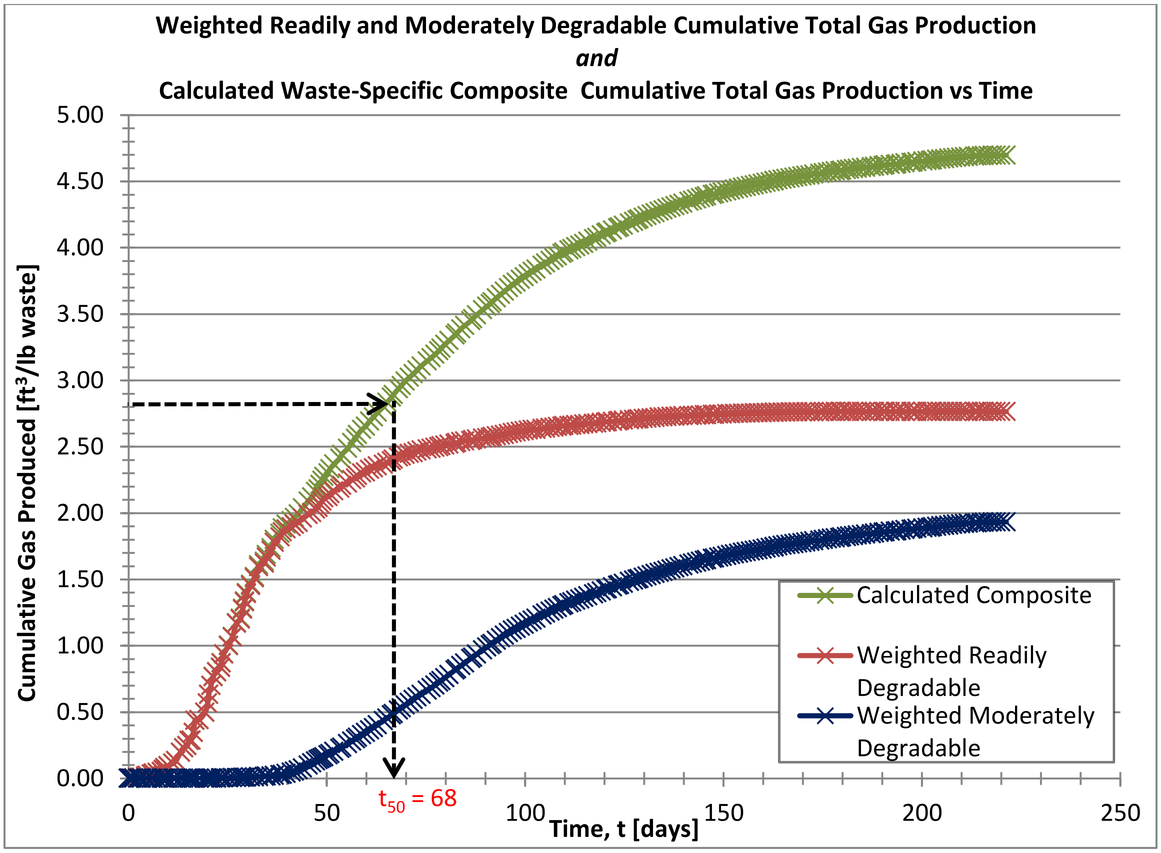

Figure 7.9 Weighted Cumulative Readily and Moderately Degradable Cumulative Gas Production and Calculated Waste-Specific Composite Gas Production versus Time

Following Step 3 of the procedure, a theoretical maximum volume of gas of 5.89 cubic feet per pound of waste was calculated using the modified Lambda method. Calculations to support this determination have been provided in Appendix H - Data and Calculations for Field Validation. The laboratory half-life (t_{50}) of the waste was determined to be 68 days based on Figure 7.9 and as specified by Step 4 of the procedure.

Using the information prepared from Step 1 through 4, a strain versus normalized t/t_{50} plot (Figure 7.10) and percent biodegradation versus normalized t/t_{50} plot (Figure 7.11) were prepared for the waste-specific composition of the Yolo County bioreactor landfill.

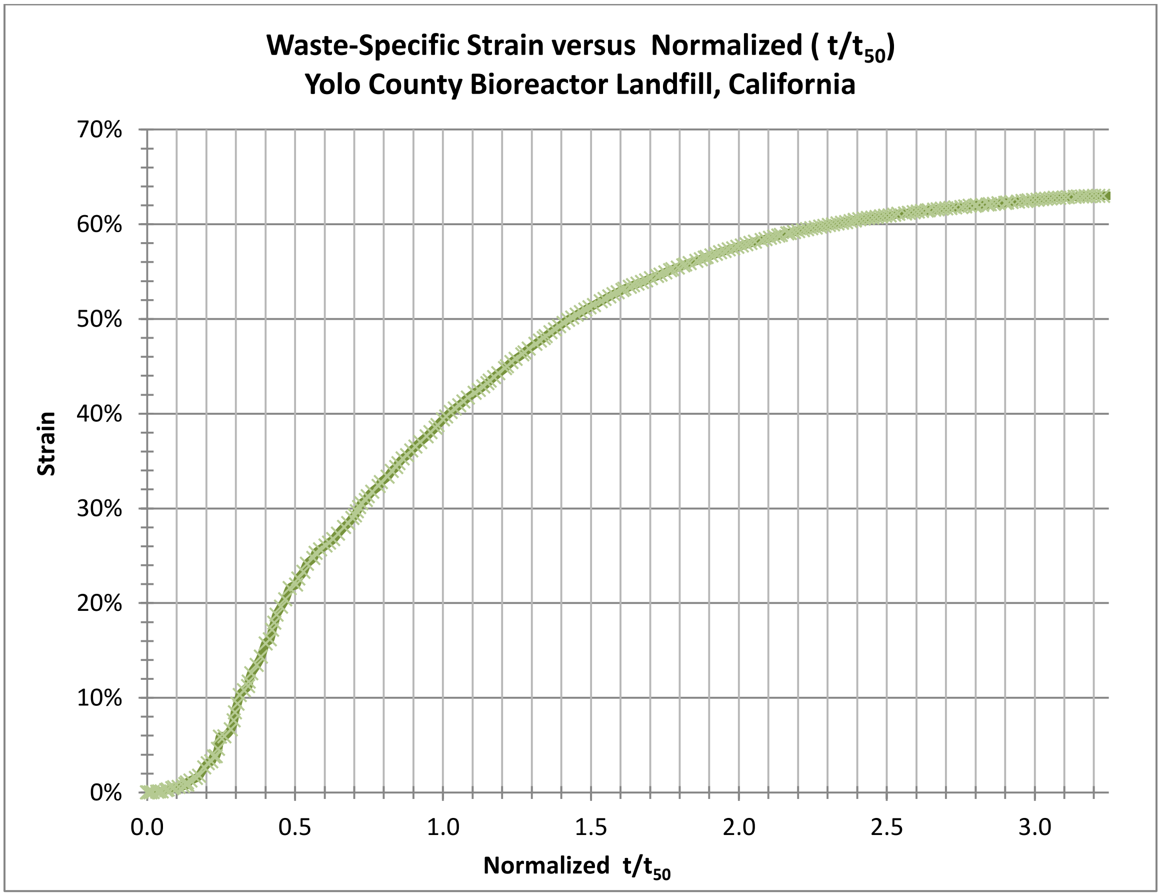

Figure 7.10 Waste-specific Strain versus Normalized t/t_{50} for Theoretical Calculation of Yolo County Bioreactor Landfill

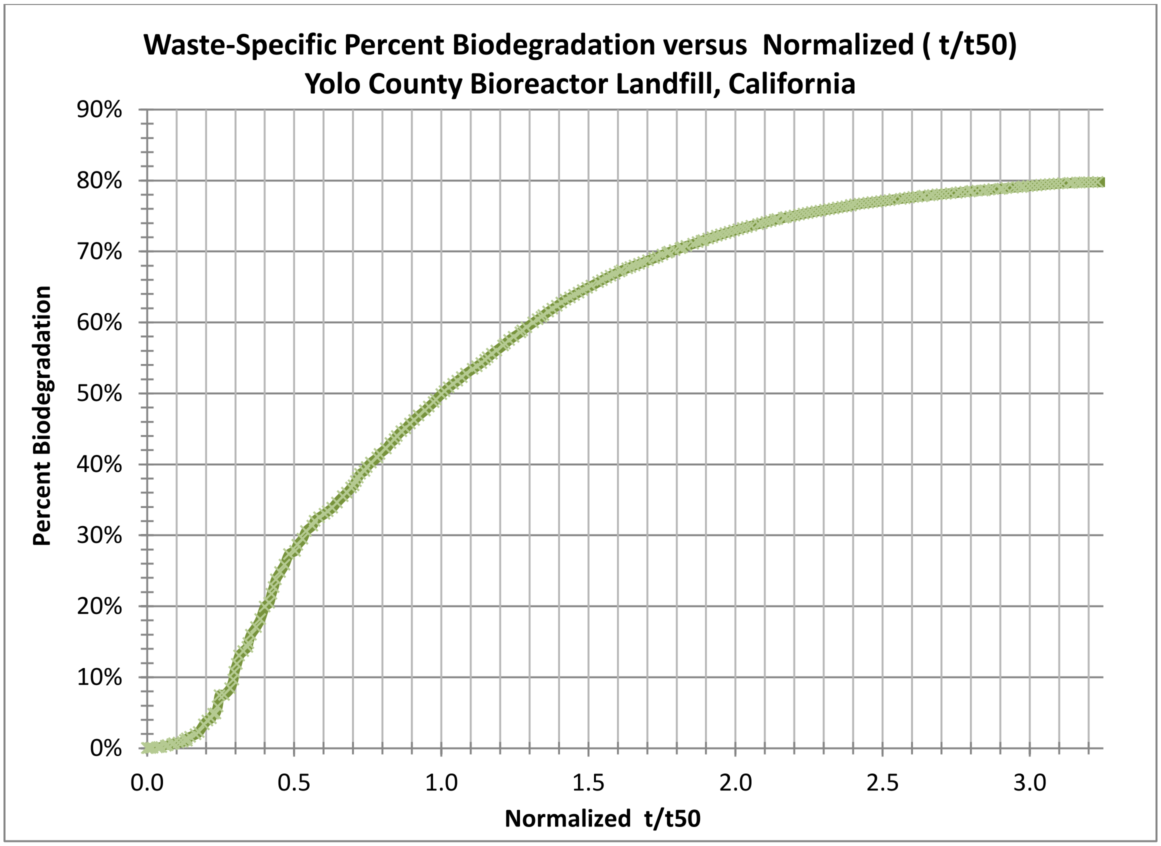

Figure 7.11 Waste-specific Percent Biodegradation versus Normalized t/t_{50} for Theoretical Calculation of Yolo County Bioreactor Landfill

The percent biodegradation versus time plot becomes nearly asymptotic at 80 percent. This trend is similar to that observed for the validation of the CMCMUA bioreactor landfill model.

Once the strain and percent biodegradation versus normalized time plots for the specific waste are determined, an analysis was conducted for each of the four layers placed within the bioreactor landfill to calculate t/t_{50}, ε_z, and %B. The approach is similar to that outlined in Table 7.3. The author has presented this analysis as Table 7.9. A half-life constant (λ) of 0.07 year^{-1} was used, resulting in a t_{50} of 10 years. This value was used as the landfill was constructed under controlled conditions.

Table 7.9 Computation of Theoretical Strain and Percent Biodegradation on Yolo County Bioreactor Landfill Using Model

Note: Step 1 through 5 (modeling landfill layer and lift thicknesses) omitted

Step 6: Determine ε_z graphically by using the normalized graph of t/t_{50} and ε_z

Figure 7.9 provided for graphical determination of ε_z based on t/t_{50}

Step 7: Final layer height, h_f [ft] = $h_i - \varepsilon_z * h_i = h_i (1-\varepsilon_z)$

Step 8: %B = $\varepsilon_z / (1-R)$ *OR* obtained graphically from %B versus t/t_{50} graph
R = percent inert fraction of waste (= 21% for example composition = 0.21)

Figure 7.10 provided for graphical determination of %B based on t/t_{50}

Step 9: A table can be created to calculate t/t_{50}, ε_z, and %B, as shown below:

Layer	**Date**	**Time, t [yr]** (Measured since Aug 2004)	**t/t_{50}**	**h_i [ft]**	**ε_z [%]**	**h_f [ft]**	**R**	**%B [%]**
1	Mar 2001	3.41	0.34	12.5	11%	11.13	0.21	14%
2	May 2001	3.24	0.32	15	10%	13.5	0.21	13%
3	Jul 2001	3.08	0.31	15	9%	13.65	0.21	12%
4	Aug 2001	3.00	0.30	7	8%	6.51	0.21	11%

Step 10: The average strain across each layer can be calculated as:

$\varepsilon_{zavg} = (\sum\varepsilon_z \times h_i)/\sum h_i$

So, $\boldsymbol{\varepsilon_{zavg}}$ = **9.6%**

Step 11: The average %B across each layer can be calculated as:

$\%B_{avg} = (\sum\%B \times h_i)/\sum h_i$

So, **$\%B_{avg}$** = **12.7%**

7.3.4 Discussion of Field and Model Data

From calculation of field data provided as Table 7.8, ε_{zfield} is determined to be approximately 8.3 percent, while ε_{zavg} from the model is 9.6 percent. Therefore, it appears the model slightly overpredicts strain an overall average basis. Likewise, from Table 7.8, $\%B_{field}$ is approximately 10.5 percent and calculated $\%B_{avg}$ is 12.7 percent.

It is observed that there is a very close correlation between field and laboratory values. Since the waste was placed within a one-year time interval, waste composition likely remained consistent; therefore, the assumption of consistent waste characterization remains valid. It is likely that the waste has been closely monitored to prevent excessive bulky goods and slowly degradable constituents.

It is also observed that the variation of prediction between field and theoretical strain and percent biodegradation using the model for the Yolo County landfill is much closer than for the CMCMUA landfill. The thickness of waste within the Yolo County bioreactor landfill is approximately half of the 100 foot waste thickness of the CMCMUA bioreactor landfill. As indicated in the discussion of CMCMUA, a variation caused by bridging and bulky goods may affect ground-level settlement from topographic surveys.

Additionally, since the landfill operates as a full-size test landfill, leachate recirculation piping and equipment, gas collection components, and remote sensing and measurement were optimized to create conditions similar to those in laboratory. Although the landfill was intended to be a full-size test, the author notes that this shows evidence that a well-controlled bioreactor landfill can successfully be used to enhance biodegradation, and that the use of this model to predict settlement and biodegradation characteristics of these types of landfills shows very good agreement with field results.

7.4 Discussion on Comparison Between Landfills for Validation

A comparison between the validation model parameters used for both validation cases is provided as Table 7.10.

Table 7.10 Comparison Between Validation Model Parameters

Comparison of Parameters Between Validation Models	CMCMUA	Yolo County
Percent Readily Degradable Waste	25%	33%
Percent Moderately Degradable Waste	43%	37%
Percent Slowly Degradable	12%	9%
Percent Inert Waste	20%	21%
Laboratory LandGEM Decay Constant, k [$year^{-1}$]	0.017	0.018
Laboratory Half-life Decay Constant, λ_{lab} [$year^{-1}$]	2.534	2.819
Field Observed Decay Constant from Settlement, λ_{field} [$year^{-1}$]	0.024	0.031
Industry Prescribed Half-life Decay Constant, $\lambda_{theoretical}$ (year-1]	0.045	0.07
Laboratory Half-life [year] based on λ_{lab}	0.27	0.25
Field Half-life based on λ_{field} [year] based on λ_{field}	28.9	22.4
Half-life from Industry Prescribed Constant, $\lambda_{theoretical}$ ($year^{-1}$)	15.4	9.9
Theoretical Gas Potential [ft^3/lb]	6.23	5.89
Laboratory-to-Field Correction Factor, $f_1 = (\lambda_{lab}/ \lambda_{field})$	0.0095	0.0110
Industry Prescribed-to-Field Correction Factor, $f_2 = (\lambda_{lab}/ \lambda_{theoretical})$	0.53	0.44

As seen from the data above, they key issue is the selection of appropriate half-life (t_{50}) and the half-life decay constant (λ). The ratio of the field observed half-life decay constant to the laboratory field half-life decay constant is represented as the laboratory-to-field correction factor, f_1. This shows that the field half-life decay factor is approximately 0.01, or 1 percent of the laboratory half-life decay constant. A ratio of the half-life constant prescribed by industry to half-life observed from field data is provided as correction factor f_2. From this work, it is observed that the field half-life is approximately 0.0485, or 50 percent of the industry prescribed half-life.

Although settlement data is available to estimate the field conditions, the industry prescribed half-life decay constant $\lambda_{theoretical}$ is used for calculations and analyses since the field observed decay constant λ_{field} is only calculated from two sets of data between comparative years. Therefore, use of this field half-life constant is therefore not a perfect fit. As stated earlier, a more representative field half-life decay constant for use in field validation would be based than data containing more than two data points.

As observed in the CMCMUA and Yolo County validations and in Figure 7.3 and 7.11, the percent biodegradation versus time plot reaches an asymptotic value equal to the proportion of the sum of the weights of the readily and moderately degradable fraction to that of the total degradable weight of MSW. It is observed that the strain and percent biodegradation plots become asymptotic at an approximate normalized t/t_{50} ratio of 3. The asymptotic value of strain ε_z is provided in Equation 7.2 shown below.

$$\varepsilon_{z_{asymptotic}} = (1-R)\frac{W_r + W_m}{W_r + W_m + W_s} \tag{7.2}$$

CHAPTER 8

SUMMARY OF WORK AND CONCLUSIONS

8.1 Summary of Work Completed

The experimental work completed included the creation and testing of multiple bioreactors simulating a landfill environment to investigate the gas production and settlement characteristics of a typical MSW bioreactor landfill. Each bioreactor was constructed in components and filled with a homogenized waste sample representative of the sample set. Four homogenized waste sample sets, composite, readily, moderately, and slowly degradable, were created and tested. A total of 16 composite bioreactors were created, along with 6 bioreactors for each of the readily, moderately, and slowly degradable sample sets. Bioreactors were connected to a gas collection system, leachate recirculation tubing, and subjected to leachate over a period of approximately 260 days to simulate a landfill environment. Gas production, settlement, and other physical and engineering parameters were measured as these conditions varied.

Bioreactors were submerged in a water bath maintained at a temperature of 110 ^{o}F, and gas collection piping was used to collect gas flow from each reactor set to a dedicated measuring device. Gas produced from the composite bioreactor set and each readily, and moderately reactors were collected using an automated gas flow meter (Sierra Instruments model MicroTrak 101) recording instantaneous methane flow rate. A tedlar gas bag, manufactured by SKC, was connected in series after each gas flow meter to record total gas volume.

A tedlar gas bag was connected directly to the slowly degradable reactor set. At periodic intervals, gas bags were also used to analyze gas composition and serve as a secondary check to the data obtained from the flow meters. Each of the gas meters was connected to a data collection to obtain daily gas production rates.

Leachate from an existing landfill was re-circulated on a weekly basis to maintain a moisture content of between 40 to 45 percent to simulate a bioreactor landfill and accelerate biodegradation. Moisture content was monitored using a PICO64 moisture content probe installed into one bioreactor representative of each of the four reactor sets. Leachate was added as needed to increase the moisture content of the waste sample to within the recommended limits.

At select intervals, individual bioreactors were decommissioned from the composite reactor to be sampled for (C+H)/L testing and used for compression testing for compression characteristics (C'_c, C_α, and C_β) of the waste at the determined biodegradation ([C+H]/L) state. The use of (C+H)/L to quantify intermediate state of biodegradation has been refuted by this work; however, compression test results were compared against those performed by Lifrieri (2010) and were shown to be in close agreement.

Following completion of the experiment, remaining operational bioreactors were decommissioned after performing a series of measurements. The intent of the measurements was to understand the change in density and loss of mass which may be attributable to biodegradation and validate the gas production models evaluated through this work.

8.2 Summary of Data Collected

The following summary is given for the laboratory work conducted herein:

1) Over a 221 day period, gas flow meters collected approximately 2.465, 4.623, and 2.860 cubic feet of methane per pound waste for the composite, readily, and moderately bioreactor sets. Secondary tedlar gas bags collected 5.332, 8.877, 5.796, and 0.078 cubic feet of total gas per pound of waste for the composite, readily, moderately, and slowly degradable bioreactor sets. Based on a 55% distribution of landfill gas as methane, the two methods of collection were within 11 percent of each and in positive agreement. The author suggests the additional volume collected by the gas bags in comparison to gas flow meters is likely due to the production and capture of trace landfill gases produced during early phases of decomposition.

2) This author notes an important clarification that theoretical gas production is based on total wet weight of the waste material as placed which follows industry standard, and not based on pound of dry waste.

3) Inclusion of plastics and synthetics in waste provides an artificial source of lignin for waste tested using the (C+H)/L test method. Testing on pairs of control and test samples confirmed that inclusion of plastic and other synthetics would act as artificial lignin and report reduced ratios of (C+H)/L.

4) Several gas production models were evaluated by this work. This work examined which model closest matched the mass degradation measured. Review of percent gas collected by flow meters and comparison to theoretical gas potential calculated by the lambda method as modified by Lifrieri (2010) produces results within a

15 percent range. Therefore, as an alternative to using actual mass degraded as suggested above, it is suggested that prediction of gas production by the lambda method as modified by Lifrieri (2010) is most suitable for estimation of gas production, to determine percent biodegraded, and to determine time to end of biodegradation.

5) The settlement due to decomposition and loss of mass can be calculated using data obtained from gas collection in concert with measurement of actual mass degradation. To determine the magnitude of biodegradation of any layer within a landfill, the use of the biodegradation ratio, B, is introduced. The ratio can be expressed as the total decomposed weight normalized by the weight of initial degradable weight. The initial degradable weight can be determined by landfill and waste stream records of the placed waste. Decomposed weight can be obtained by testing such as loss on ignition at 550 °C as per ASTM D7348 - "Standard Test Methods for Loss on Ignition (LOI) of Solid Combustion Residues". By knowing B and the inert weight ratio, R, the change in layer height can be calculated and likewise vertical strain.

6) Validation models against both a landfill with waste characterization tested herein and a landfill with differing composition indicated a good correlation between field-observed conditions and theoretical analyses. It is commented that one of the key factors affecting bioreactor landfills and laboratory-to-field scaling is the availability of nutrients and leachate. The leachate and nutrient have a sizeable influence on waste half-life, and therefore have a direct impact on the half-life decay factor for evaluation of percent biodegradation and strain.

8.3 Conclusions

The following conclusions are drawn from the laboratory work conducted herein and evaluation of the data and model:

1) A single decay constant modifier, k_c, for a waste of any composition can be estimated by characterizing the mixed waste into representative fractions of readily, moderately, and slowly biodegradable components and taking the weighted average of each decay constant. The data presented by Lifrieri (2010) supports this conclusion. This validates one of the hypotheses proposed by this author through his "Proposal for Dissertation". For instance, component modifiers k_r= 0.045, k_m = 0.012, and k_s= 0.0021 year^{-1}, for the readily, moderately, and slowly degradable waste types were obtained from this work. Using the waste profile for composite waste, a calculated composite decay modifier, k_c , of 0.0167 year^{-1}was obtained. This is in close agreement with the observed actual composite k of 0.0170 year^{-1} from the composite bioreactor and validates the theory supporting the calculation of a waste-specific modifier by proportioned fractions. As discussed in this work, the contribution of slowly degradable fraction can be neglected and is provides an insignificant (less than 1 percent) contribution to the overall decay constant and characteristics of the waste.

2) The ratio of the cumulative volume of gas produced at time "t" and total gas potential, can relate to the percent biodegradation of the waste material at any time "t". The state of decomposition can also be quantified by taking the ratio of the degradable weight at any time to the initial degradable weight. Therefore, the percent biodegradation can be determined from records of gas collection, by testing for percent

organic solids, or field-measurement of settlement at the operational landfill taken at two or more discrete time intervals.

3) The use of (C+H)/L to quantify the state of biodegradation was originally proposed; however, its use to predict state of biodegradation in an intermediate state has been contradicted by the results of this work. Substantial discussions on limitations have been provided in Chapter 5, which indicate interferences in the test in measurement of lignin result in the method providing mixed correlation to determine the projected end of substantial biodegradation. Instead, a correlation with loss of mass to determine state of biodegradation of the waste was proposed and advanced by this work.

4) Relationships for biodegradation in terms of volume and mass were defined through this work as summarized above. A predictive model based on the understanding of this phenomenon was developed to identify relationships between volume, mass, and strain, by which characteristic curves for any waste composition could be determined. These characteristics curves allow for the prediction of percent biodegradation and vertical strain as functions of time for a given composition of MSW.

It was the intent of this work to attempt to identify the state of biodegradation of MSW, and to create a model to relate laboratory to field estimates of the magnitude and rate of gas production and biodegradation settlement for a MSW landfill with any waste composition. The intent was accomplished through this study.

CHAPTER 9

RECOMMENDATIONS FOR FUTURE WORK AND ORIGINALITY OF WORK

9.1 Summary

Through the process of this work, the author has gained insight to provide recommendations for additional work to confirm and improve the efficiency of the model suggested herein. The following suggestions have arisen:

1. As waste is inherently heterogeneous, some portion of the waste may decompose at a variable rate; therefore the author recommends performing sensitivity analyses on the waste composition to create an upper and lower-bound value for the single-decay constant modifier, k_c, when employing the method in practice. Additionally, the waste could be categorized into intermediate categories, for example intermediate readily, intermediate moderately, intermediate slowly, or as many degradable time-dependent categories desired to create a more accurate single-decay constant modifier. Also, it has been demonstrated that the weighted average concept of determining decay factors is valid. The author suggests that different sources of waste within each category, for example fat and protein-based food or electronics, be tested to understand the effect of variations within each category.

2. When performing laboratory analysis of a specific waste type, additional bioreactors should be created and subject to identical conditions, but these sacrificial bioreactors should be removed at various intervals to perform destructive testing to determine mass loss, change in density, and moisture.

If waste appears to have a distinguishable appearance, it may be possible to separate the waste back into readily, moderately, and slowly waste categories and weight each fraction to approximate percent decomposition of each individual fraction as time progresses.

3. The author comments that the use of half-life decay modifiers suggested by Findikakis and Leckie (1979) and Durmesoglu (2005) to predict time rate of settlement for bioreactor landfills is not suitable. While total gas production may be estimated using these factors, the author remarks that the half-lives suggested by Findikakis are based on a traditional landfill process. The nature of the bioreactor environment inherently suggests that the waste would degrade at a more rapid rate, thereby decreasing the waste half-life time and increasing the half-life decay modifier as shown by this work. The author suggests that gas collection records, as well as waste placement, lift thickness, and composition records, from bioreactor or leachate recirculation landfills in operation for 15 years or longer should be utilized to predict new half-life times. Consequently, the data would support the generation of half-life decay modifiers which may be comparable to this work.

4. As composition of landfill gas changes with time, a more accurate estimate of gas volume collected may be possible if the percent of each gas as a portion of total gas is known at any given time. The author recommends a gas flow meter capable of measuring flow rate from multiple gases, including trace landfill gases, be utilized for gas collection for future collection and testing. Alternately, the gas flow meter should be connected permanently to a gas composition meter such as the Landtec GEM 2000+ used in this work, or other meter with ability to determine gas composition at any given time.

5. To date, researchers have not reported studies on how to correlate laboratory measurements of the half-life decay constant to field conditions. The author suggests that laboratory studies based on field-observed conditions be completed to understand the variation and relate the two scenarios. It is the author's opinion that work conducted towards this effect will lead to substantial contribution to the state-of-the-practice. It will also help refine gas production models which allow industry to perform cost-benefit decisions to support landfill gas-to-energy conversion

9.2 Originality of Work

To-date in prior works, researchers and practitioners have employed empirical models based on mechanical processes to simulate and predict biodegradation settlement. This work is unique in its review and detailed understanding of biodegradation as a chemical phenomenon, and the development of a model based on this understanding.

Original concepts, including the percent biodegradation expressions developed in Chapter 6 and degradability modifiers, have been developed through this work. All lab studies are based on mechanisms taking place in one layer; however, in the field, waste is place in multiple layers at different times. This results in varying states of biodegradation for each layer. The model produced here takes this consideration into account by suggesting a procedure for determining the average biodegradation across the entire landfill.

A detailed review of existing gas production models was undertaken, which allow for a comparison of theoretical models to actual gas production. This will allow for more accurate and realistic gas production estimate, and provides practitioners guidance on selection of a preferred model for design basis. Likewise, the work has also shown that measurement of degradable weight loss does provide an approximate measure of state of biodegradation. This work has created a waste-specific model which overcomes the shortcoming of other models which are empirical and consider a wide set of data including variable landfill types, thicknesses, climatic environments, and waste composition.

Although the work herein simulated MSW landfills with bioreactor technology, the model can also be used for traditional landfills by simply varying the half-life and half-life modifier for analyses.

The author is unaware of any other work which unifies gas production, determination of mass loss, and field settlement to create a model to determine the state of biodegradation and strain (settlement) at any given time. The flexibility of this developed model makes is easy for engineers and practitioners to conduct waste- and location-specific analyses of MSW landfills, however the concepts and simplicity of the theory behind the model make it approachable for regulators, clients, and general public.

The work has also provided an enhanced understanding of the biodegradation process. This will create numerous research opportunities which can further the state-of-the-art and practice of prediction for MSW landfills.

APPENDIX A

BIOREACTOR AND EXPERIMENT COMISSIONING RECORDS

Appendix A contains records maintained during the creation of bioreactors and pictures taken of the experimental set up during commissioning.

A.1 Bioreactor Assembly Records

Tables A.1.1 through A.1.4 tabulate record the weights of constituents comprising each of the 34 bioreactors used in this experiment. A tabletop digital scale (model CL2000 by Ohaus) was used to record the weight of each constituent. Constituents were weighed individually, placed into a marked zip-lock bag indicating bioreactor number and measured weight, and then grouped with other constituents of the same bioreactor. Constituents were mixed and moisture conditioned prior to placement into each respective bioreactor. The process is depicted further by Figures A.3.10 through A.3.26 contained herein.

Table A.1.1 Assembly Records for Composite Bioreactors

No.	Paper	Yard Waste	Wood	Plastic	Textile	Glass	Food	Soil	Metal	Total
Ideal [lb]:	**0.8**	**0.13**	**0.04**	**0.26**	**0.06**	**0.23**	**0.4**	**0.17**	**0.01**	**2.10**
C-1	0.80	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.10**
C-2	0.81	0.13	0.04	0.26	0.06	0.24	0.40	0.17	0.01	**2.12**
C-3	0.81	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.11**
C-4	0.80	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.11**
C-5	0.80	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.11**
C-6	0.80	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.11**
C-7	0.81	0.13	0.04	0.26	0.06	0.24	0.40	0.17	0.01	**2.11**
C-8	0.80	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.11**
C-9	0.80	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.11**
C-10	0.80	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.11**
C-11	0.80	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.11**
C-12	0.80	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.11**
C-13	0.81	0.13	0.04	0.26	0.06	0.24	0.40	0.17	0.01	**2.11**
C-14	0.81	0.13	0.04	0.26	0.06	0.24	0.40	0.17	0.01	**2.12**
C-15	0.81	0.13	0.04	0.26	0.06	0.23	0.40	0.17	0.01	**2.11**
C-16	0.80	0.13	0.04	0.26	0.06	0.24	0.40	0.17	0.01	**2.11**

Table A.1.2 Assembly Records for Readily Degradable Biodegradable Bioreactors

No.	Paper	Yard Waste	Wood	Plastic	Textile	Glass	Food	Soil	Metal	Total
Ideal [lb]:	**-**	**0.50**	**-**	**-**	**-**	**-**	**1.60**	**-**		**2.10**
R-1	-	0.51	-	-	-	-	1.60	-		**2.11**
R-2	-	0.50	-	-	-	-	1.60	-		**2.10**
R-3	-	0.50	-	-	-	-	1.60	-		**2.10**
R-4	-	0.51	-	-	-	-	1.60	-		**2.11**
R-5	-	0.51	-	-	-	-	1.60	-		**2.11**
R-6	-	0.51	-	-	-	-	1.60	-		**2.11**

Table A.1.3 Assembly Records for Moderately Biodegradable Bioreactors

No.	Paper	Yard Waste	Wood	Plastic	Textile	Glass	Food	Soil	Metal	Total
Ideal [lb]:	**1.86**	**-**	**0.10**	**-**	**0.14**	**-**	**-**	**-**		**2.10**
M-1	1.88	-	0.10	-	0.13	-	-	-		**2.11**
M-2	1.88	-	0.10	-	0.13	-	-	-		**2.11**
M-3	1.88	-	0.10	-	0.13	-	-	-		**2.12**
M-4	1.87	-	0.10	-	0.13	-	-	-		**2.10**
M-5	1.87	-	0.10	-	0.13	-	-	-		**2.11**
M-6	1.87	-	0.10	-	0.13	-	-	-		**2.11**

Table A.1.4 Assembly Records for Slowly Biodegradable Bioreactors

No.	Paper	Yard Waste	Wood	Plastic	Textile	Glass	Food	Soil	Metal	Tot al
Ideal [lb]:	**-**	**-**	**-**	**1.30**	**-**	**-**	**-**	**0.80**		**2.10**
S-1	-	-	-	1.30	-	-	-	0.82		**2.12**
S-2	-	-	-	1.30	-	-	-	0.81		**2.11**
S-3	-	-	-	1.30	-	-	-	0.82		**2.12**
S-4	-	-	-	1.30	-	-	-	0.81		**2.11**
S-5	-	-	-	1.30	-	-	-	0.81		**2.11**
S-6	-	-	-	1.30	-	-	-	0.82		**2.12**

A.2 Moisture Conditioning Records

Leachate was added to each sample to achieve a targeted moisture content of approximately 170 percent by weight to ensure leachate generation by exceeding the waste's field capacity. Tables A.2.1 through A.2.4 tabulate leachate added to each sample prior to placement into bioreactors.

Table A.2.1 Moisture Conditioning Records for Composite Bioreactors

Reactor No.	Wt of Bag [lbs]	Wt of Bag [lb]	Initial Moisture Content [%]	Dry Weight [lb]	Amount of Water to Add [lb]	Weight of Sample @ 170% MC	Weight of Sample + Bag @ 170% M.C.
C-1	0.08	2.45	43.20	1.71	2.91	4.62	4.63
C-2	0.08	2.49	44.90	1.72	2.92	4.63	4.64
C-3	0.08	2.45	43.10	1.71	2.91	4.62	4.65
C-4	0.08	2.53	47.00	1.72	2.92	4.64	4.65
C-5	0.08	2.54	47.50	1.72	2.92	4.64	4.65
C-6	0.08	2.51	46.30	1.72	2.92	4.64	4.65
C-7	0.08	2.46	43.70	1.71	2.91	4.62	4.63
C-8	0.08	2.53	47.40	1.72	2.92	4.64	4.65
C-9	0.08	2.38	39.60	1.70	2.90	4.60	4.61
C-10	0.08	2.49	45.40	1.72	2.92	4.63	4.64
C-11	0.08	2.40	40.70	1.71	2.90	4.61	4.62
C-12	0.08	2.38	39.70	1.71	2.90	4.60	4.61
C-13	0.08	2.24	32.70	1.69	2.87	4.56	4.57
C-14	0.08	2.29	35.10	1.69	2.88	4.57	4.58
C-15	0.08	2.28	34.60	1.69	2.88	4.57	4.58
C-16	0.08	2.23	32.30	1.69	2.87	4.56	4.57

Table A.2.2 Moisture Conditioning Records for Readily Degradable Bioreactors

Reactor No.	Weight of Bag [lbs]	Weight of Bag [lb]	Initial Moisture Content [%]	Dry Weight [lb]	Amount of Water to Add [lb]	Weight of Sample @ 170% M.C. [lb]	Weight of Sample + Bag @ 170% M.C. [lb]
R-1	0.08	4.02	136.80	1.70	2.89	4.59	4.60
R-2	0.08	3.46	81.80	1.90	3.24	4.14	5.15
R-3	0.08	3.24	61.80	2.00	3.40	5.40	5.41
R-4	0.08	3.66	89.00	1.94	3.29	5.23	5.24
R-5	0.08	3.18	57.60	2.02	3.43	5.45	5.46
R-6	0.08	3.48	81.00	1.92	3.27	5.19	5.20

Table A.2.3 Moisture Conditioning Records for Moderately Degradable Bioreactors

Reactor No.	Weight of Bag [lbs]	Weight of Bag [lb]	Initial Moisture Content [%]	Dry Weight [lb]	Amount of Water to Add [lb]	Weight of Sample @ 170% M.C. [lb]	Weight of Sample + Bag @ 170% M.C. [lb]
M-1	0.08	2.01	3.60	1.94	3.30	5.24	5.25
M-2	0.08	2.02	3.80	1.94	3.30	5.24	5.25
M-3	0.08	2.02	4.00	1.94	3.30	5.24	5.25
M-4	0.08	2.00	5.60	1.90	3.23	5.12	5.13
M-5	0.08	2.03	4.70	1.94	3.30	5.24	5.25
M-6	0.08	2.01	3.60	1.94	3.30	5.24	5.25

Table A.2.4 Moisture Conditioning Records for Slowly Degradable Bioreactors

Reactor No.	Weight of Bag [lbs]	Weight of Bag [lb]	Initial Moisture Content [%]	Dry Weight [lb]	Amount of Water to Add [lb]	Weight of Sample @ 170% M.C. [lb]	Weight of Sample + Bag @ 170% M.C. [lb]
S-1	0.08	1.97	17.20	1.68	2.85	4.53	4.54
S-2	0.08	1.98	21.20	1.63	2.78	4.41	4.42
S-3	0.08	1.96	23.60	1.59	2.70	4.29	4.30
S-4	0.08	1.98	21.50	1.63	2.78	4.41	4.40
S-5	0.08	1.98	18.10	1.68	2.85	4.53	4.54
S-6	0.08	1.99	21.70	1.63	2.78	4.41	4.42

A.3 Photo Log for Test Set Up

The following Figures have been provided to illustrate the process completed to construct, calibrate, and assemble the test set-up and bioreactors used for this experiment. Example instructions and forms used by author to guide establishment of bioreactors are included under Appendix E.1 – Work Plan and Testing Instructions and E.2 – Standard Forms Used for Commissioning Bioreactors and Test Equipment. A list of parts used to construct the set-up has been provided under Appendix E.4 – Parts List

Figure A.3.1 Assembled Consolidation Machines and Data Acquisition

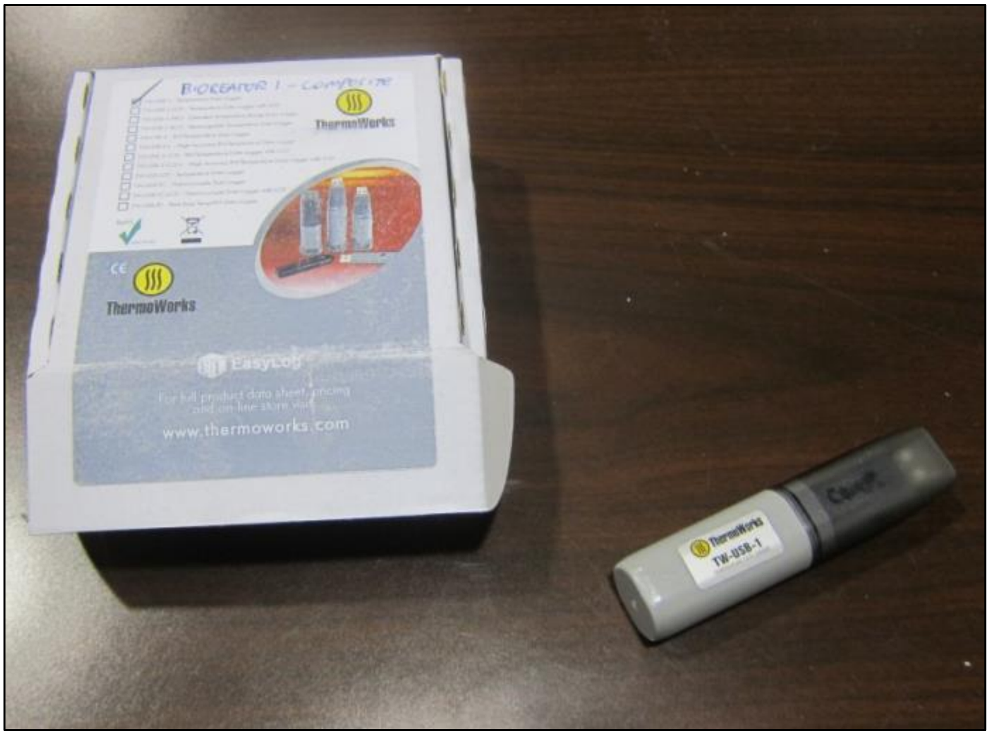

Figure A.3.2 Temperature Sensor for Water Bath

Figure A.3.3 Tank Heater for Water Bath

Figure A.3.4 Assembled Bioreactor

Figure A.3.5 Connection of Bioreactor Gas Collection Piping in Series

Figure A.3.6 Gas Totalizers for Methane Volume Determination

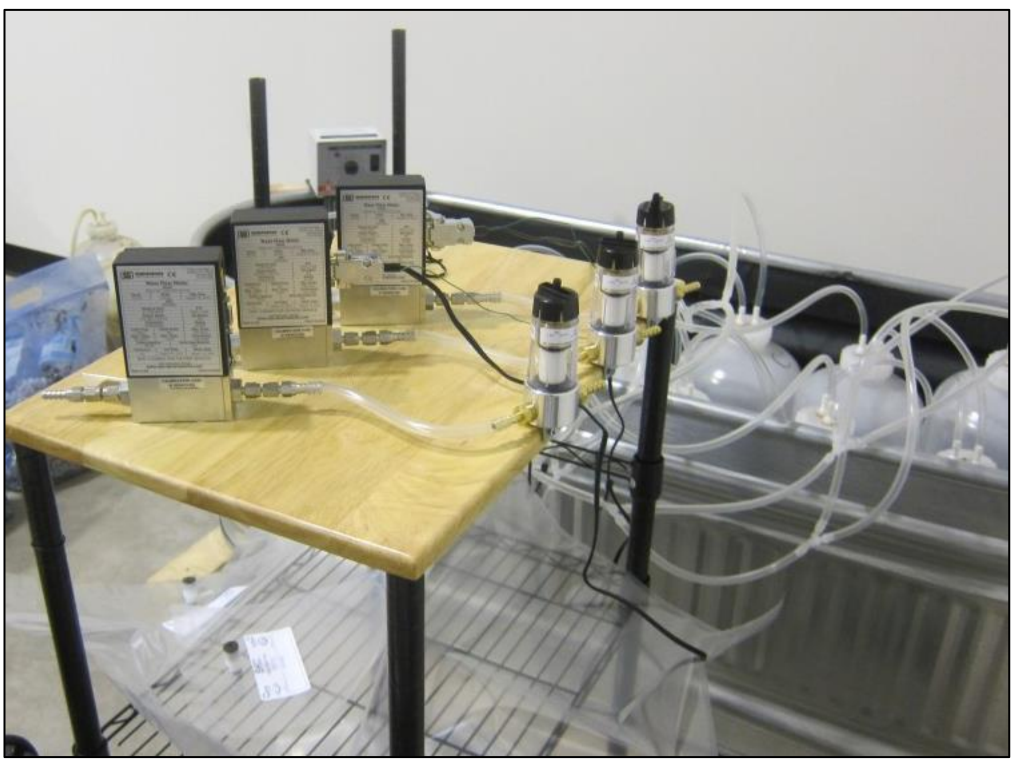

Figure A.3.7 Gas Totalizers Connected to Bioreactors

Figure A.3.8 Recirculation Pump for Water Bath

Figure A.3.9 Application of Anti-algae, anti-foam powder to water bath

Figure A.3.10 Preparation to Weigh Constituents for Bioreactors

Figure A.3.11 Weighing of Plastic Constituents

Figure A.3.12 Batching Constituents (Plastics shown) for Bioreactor Assembly

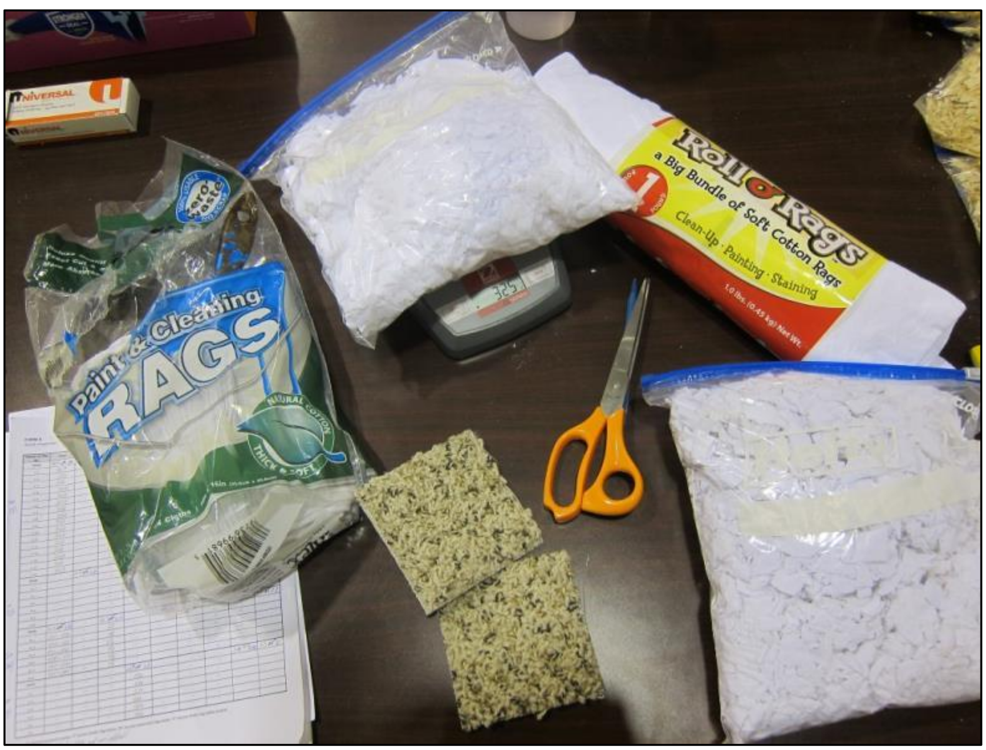

Figure A.3.13 Shredded Textiles and Synthetics Used for Bioreactors

Figure A.3.14 Shredded Paper, Newsprint, Magazines, and Craft Paper Used for Bioreactors

Figure A.3.15 Food Waste Used for Bioreactors

Figure A.3.16 Yard Waste Used for Bioreactors

Figure A.3.17 Soil Used for Bioreactors

Figure A.3.18 Crushed Glass Used for Bioreactor

Figure A.3.19 Batching All Components for Bioreactor Mixing

Figure A.3.20 Preparing Constituents for Mixing

Figure A.3.21 Organizing Composite Constituents based on Bioreactor Number for Mixing

Figure A.3.22 Organizing Readily Degradable Constituents based on Bioreactor Number for Mixing

Figure A.3.23 Organizing Moderately Degradable Constituents based on Bioreactor Number for Mixing

Figure A.3.24 Organizing Slowly Degradable Constituents based on Bioreactor Number for Mixing

Figure A.3.25 Mixing Components to Create Bioreactor-specific Waste Mixture

Figure A.3.26 Mixed Wastes for Bioreactors

Figure A.3.27 Placement of Gravel Drainage Layer

Figure A.3.28 Cutting of Geotextile Fabric Filter Layer

Figure A.3.29 Compaction of Waste into Bioreactor Using Tamping Rod

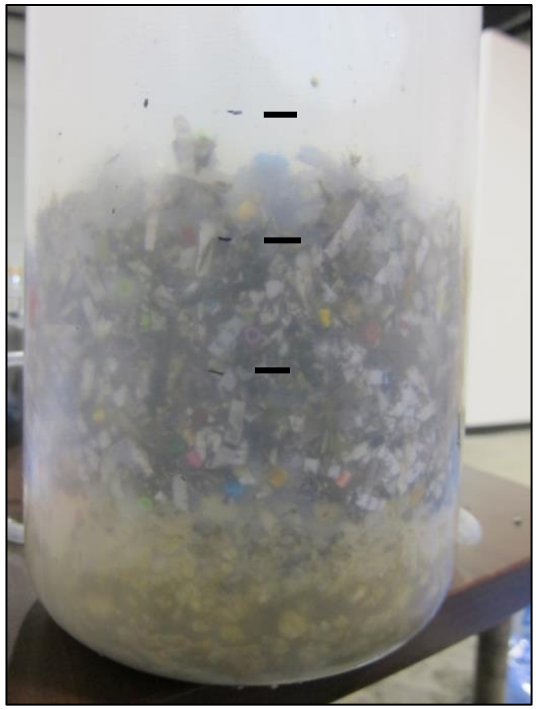

Figure A.3.30 Compacted Waste (note black marks used for lift thickness and measure density)

Figure A.3.31 Reactor Tank Assembled (Composite- Right, Individual – Left)

Figure A.3.2 Final Assembled Test Set Up

APPENDIX B

RECORDS MAINTAINED DURING EXPERIMENT

Appendix B contains data and records collected throughout the course of the experiment.

B.1 Water Bath Temperature Logs

Table B.1.1 and B.1.2 tabulates water bath temperature readings recorded throughout the course of this research. One submersible electronic USB data logger (model TW-USB-1 by Thermoworks) was placed in each of the bioreactor tanks. A manual general purpose thermometer was utilized periodically to verify the electronic temperature gage. The equipment allowed for an acoustic alarm to be set when temperature exceeded or dropped below a preset threshold. A high alarm was set at 115 ^{o}F and a low alarm was set at 105 ^{o}F

Temperature was maintained using a water tank heater (model H-2986A, 110V by Humboldt) attached to the bioreactor. The tank heater was thermostatically controlled and adjustable to warm up to a maximum temperature of 200 ^{o}F. Water was circulated in each tank using a submersible medium pond pump (model 7301710 by Beckett) to promote uniform temperature throughout the tank.

Water baths were maintained at an average temperature of 110 ^{o}F to simulate ambient temperatures within a landfill environment and support enhanced mesophilic reactions.

Table B.1.1 Record of Water Bath Temperatures – Composite Tank

Water Bath Temperature Record - Composite Reactor Set				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
11/12/13	-	64	67	
11/13/13	-	72	74	
11/14/13	-	77	81	
11/15/13	-	83	88	
11/16/13	-	92	97	
11/17/13	-	106	109	
11/18/13	0	112	110	
11/19/13	1	111	109	
11/20/13	2	111	111	
11/21/13	3	110	112	112
11/22/13	4	110	110	
11/23/13	5	110	112	
11/24/13	6	111	109	
11/25/13	7	110	111	
11/26/13	8	109	111	
11/27/13	9	111	112	
11/28/13	10	112	112	
11/29/13	11	112	111	
11/30/13	12	111	111	
12/1/13	13	110	112	
12/2/13	14	110	109	
12/3/13	15	110	111	
12/4/13	16	111	110	
12/5/13	17	112	110	
12/6/13	18	111	110	
12/7/13	19	110	109	
12/8/13	20	109	112	
12/9/13	21	111	109	
12/10/13	22	110	111	110
12/11/13	23	110	111	
12/12/13	24	111	110	
12/13/13	25	110	109	
12/14/13	26	110	110	
12/15/13	27	111	110	
12/16/13	28	110	110	

Table B.1.1 Record of Water Bath Temperatures – Composite Tank (Continued)

Water Bath Temperature Record - Composite Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
12/17/13	29	110	109	
12/18/13	30	110	111	
12/19/13	31	110	112	
12/20/13	32	109	111	
12/21/13	33	111	110	
12/22/13	34	109	110	
12/23/13	35	109	110	
12/24/13	36	111	111	
12/25/13	37	110	112	
12/26/13	38	110	111	
12/27/13	39	109	110	
12/28/13	40	111	109	109
12/29/13	41	110	110	
12/30/13	42	112	110	
12/31/13	43	109	110	
1/1/14	44	111	111	
1/2/14	45	111	111	
1/3/14	46	112	109	
1/4/14	47	112	111	
1/5/14	48	111	111	
1/6/14	49	111	109	
1/7/14	50	110	109	
1/8/14	51	110	109	
1/9/14	52	110	111	
1/10/14	53	109	110	
1/11/14	54	111	110	
1/12/14	55	110	109	
1/13/14	56	110	111	
1/14/14	57	111	110	
1/15/14	58	112	112	
1/16/14	59	109	109	109
1/17/14	60	109	111	
1/18/14	61	112	111	
1/19/14	62	111	112	
1/20/14	63	110	112	

Table B.1.1 Record of Water Bath Temperatures – Composite Tank (Continued)

Water Bath Temperature Record - Composite Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
1/21/14	64	111	110	
1/22/14	65	109	110	
1/23/14	66	109	109	
1/24/14	67	111	111	
1/25/14	68	110	110	
1/26/14	69	110	110	
1/27/14	70	111	109	
1/28/14	71	109	111	
1/29/14	72	109	110	
1/30/14	73	110	111	111
1/31/14	74	110	111	
2/1/14	75	110	109	
2/2/14	76	111	109	
2/3/14	77	111	110	
2/4/14	78	109	109	
2/5/14	79	109	110	
2/6/14	80	110	111	
2/7/14	81	109	111	
2/8/14	82	110	111	
2/9/14	83	111	110	
2/10/14	84	111	109	
2/11/14	85	112	109	
2/12/14	86	109	110	
2/13/14	87	111	109	
2/14/14	88	110	110	
2/15/14	89	110	110	
2/16/14	90	110	109	
2/17/14	91	109	111	
2/18/14	92	112	111	
2/19/14	93	109	110	
2/20/14	94	110	109	110
2/21/14	95	110	111	
2/22/14	96	110	111	
2/23/14	97	111	110	
2/24/14	98	111	111	

Table B.1.1 Record of Water Bath Temperatures – Composite Tank (Continued)

Water Bath Temperature Record - Composite Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
2/25/14	99	109	111	
2/26/14	100	111	109	
2/27/14	101	110	110	
2/28/14	102	111	109	
3/1/14	103	111	111	
3/2/14	104	109	110	
3/3/14	105	109	110	
3/4/14	106	110	111	
3/5/14	107	109	111	
3/6/14	108	110	109	
3/7/14	109	110	109	
3/8/14	110	109	110	
3/9/14	111	111	109	
3/10/14	112	111	110	
3/11/14	113	110	110	
3/12/14	114	109	109	
3/13/14	115	111	111	
3/14/14	116	111	111	
3/15/14	117	112	110	111
3/16/14	118	109	109	
3/17/14	119	109	109	
3/18/14	120	111	110	
3/19/14	121	112	110	
3/20/14	122	110	109	
3/21/14	123	109	112	
3/22/14	124	111	110	
3/23/14	125	112	109	
3/24/14	126	111	111	
3/25/14	127	111	112	
3/26/14	128	109	110	
3/27/14	129	112	109	
3/28/14	130	110	110	
3/29/14	131	109	109	
3/30/14	132	111	110	
3/31/14	133	110	109	109

Table B.1.1 Record of Water Bath Temperatures – Composite Tank (Continued)

Water Bath Temperature Record - Composite Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
4/1/14	134	110	109	
4/2/14	135	111	110	
4/3/14	136	111	109	
4/4/14	137	109	110	
4/5/14	138	109	110	
4/6/14	139	110	109	
4/7/14	140	109	111	
4/8/14	141	110	111	
4/9/14	142	109	110	
4/10/14	143	110	109	
4/11/14	144	110	111	
4/12/14	145	109	111	
4/13/14	146	112	112	
4/14/14	147	110	109	
4/15/14	148	109	111	
4/16/14	149	111	110	
4/17/14	150	112	110	
4/18/14	151	110	111	
4/19/14	152	111	111	
4/20/14	153	110	109	
4/21/14	154	109	110	110
4/22/14	155	111	110	
4/23/14	156	111	112	
4/24/14	157	111	111	
4/25/14	158	111	109	
4/26/14	159	112	112	
4/27/14	160	109	111	
4/28/14	161	111	110	
4/29/14	162	110	111	
4/30/14	163	111	111	
5/1/14	164	112	109	
5/2/14	165	109	109	109
5/3/14	166	111	111	
5/4/14	167	111	111	
5/5/14	168	110	110	

Table B.1.1 Record of Water Bath Temperatures – Composite Tank (Continued)

Water Bath Temperature Record - Composite Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
5/6/14	169	110	110	
5/7/14	170	109	111	
5/8/14	171	110	111	
5/9/14	172	110	109	
5/10/14	173	110	109	
5/11/14	174	112	111	
5/12/14	175	111	109	
5/13/14	176	109	109	
5/14/14	177	112	110	
5/15/14	178	111	110	
5/16/14	179	110	109	
5/17/14	180	111	110	
5/18/14	181	111	110	
5/19/14	182	109	110	
5/20/14	183	109	109	
5/21/14	184	111	111	111
5/22/14	185	111	109	
5/23/14	186	111	110	
5/24/14	187	109	110	
5/25/14	188	110	109	
5/26/14	189	109	112	
5/27/14	190	111	110	
5/28/14	191	111	109	
5/29/14	192	111	111	
5/30/14	193	111	112	
5/31/14	194	112	110	
6/1/14	195	109	111	
6/2/14	196	111	110	
6/3/14	197	110	109	
6/4/14	198	109	111	
6/5/14	199	111	111	
6/6/14	200	111	111	
6/7/14	201	111	111	
6/8/14	202	110	111	
6/9/14	203	110	110	

Table B.1.1 Record of Water Bath Temperatures – Composite Tank (Continued)

Water Bath Temperature Record - Composite Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
6/10/14	204	111	109	
6/11/14	205	110	110	
6/12/14	206	109	110	
6/13/14	207	110	109	
6/14/14	208	110	110	110
6/15/14	209	109	110	
6/16/14	210	110	109	
6/17/14	211	110	110	
6/18/14	212	109	110	
6/19/14	213	110	109	
6/20/14	214	110	110	
6/21/14	215	110	110	
6/22/14	216	109	110	
6/23/14	217	111	109	
6/24/14	218	110	111	
6/25/14	219	110	112	
6/26/14	220	110	111	
6/27/14	221	109	110	
6/28/14	222	109	109	
6/29/14	223	110	111	
6/30/14	224	110	111	
7/1/14	225	111	111	111
7/2/14	226	110	109	
7/3/14	227	111	110	
7/4/14	228	111	109	
7/5/14	229	110	111	
7/6/14	230	109	111	
7/7/14	231	109	111	
7/8/14	232	110	111	
7/9/14	233	109	112	
7/10/14	234	111	109	
7/11/14	235	112	111	
7/12/14	236	109	110	
7/13/14	237	109	109	
7/14/14	238	111	110	

Table B.1.1 Record of Water Bath Temperatures – Composite Tank (Continued)

Water Bath Temperature Record - Composite Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
7/15/14	239	110	110	
7/16/14	240	110	109	
7/17/14	241	110	110	
7/18/14	242	109	111	
7/19/14	243	111	110	111
7/20/14	244	110	110	
7/21/14	245	110	109	
7/22/14	246	109	111	
7/23/14	247	111	110	
7/24/14	248	110	110	
7/25/14	249	110	110	
7/26/14	250	110	110	
7/27/14	251	110	109	
7/28/14	252	109	112	
7/29/14	253	112	110	
7/30/14	254	111	109	
7/31/14	255	111	111	
8/1/14	256	111	112	
8/2/14	257	109	110	
8/3/14	258	109	111	
8/4/14	259	111	110	
8/5/14	260	110	110	110
8/6/14	261	111	111	
8/7/14	262	110	110	110

Table B.1.2 Record of Water Bath Temperatures – Individual Tank

Water Bath Temperature Record - Individual Reactor Set				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
11/12/13	-	66	68	
11/13/13	-	72	76	
11/14/13	-	78	82	
11/15/13	-	84	89	
11/16/13	-	93	96	
11/17/13	-	101	106	
11/18/13	0	110	110	
11/19/13	1	110	110	
11/20/13	2	111	110	
11/21/13	3	110	110	110
11/22/13	4	111	111	
11/23/13	5	111	110	
11/24/13	6	110	109	
11/25/13	7	110	111	
11/26/13	8	112	109	
11/27/13	9	111	109	
11/28/13	10	110	110	
11/29/13	11	110	110	
11/30/13	12	111	109	
12/1/13	13	110	109	
12/2/13	14	111	110	
12/3/13	15	112	111	
12/4/13	16	109	109	
12/5/13	17	110	109	
12/6/13	18	110	111	
12/7/13	19	110	111	
12/8/13	20	111	110	
12/9/13	21	110	111	
12/10/13	22	110	110	110
12/11/13	23	111	110	
12/12/13	24	111	110	
12/13/13	25	109	109	
12/14/13	26	109	110	
12/15/13	27	110	110	
12/16/13	28	109	110	

Table B.1.2 Record of Water Bath Temperatures – Individual Tank (Continued)

Water Bath Temperature Record - Individual Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
12/17/13	29	110	109	
12/18/13	30	110	111	
12/19/13	31	109	110	
12/20/13	32	111	110	
12/21/13	33	111	110	
12/22/13	34	110	109	
12/23/13	35	111	111	
12/24/13	36	110	110	
12/25/13	37	109	110	
12/26/13	38	110	111	
12/27/13	39	111	111	
12/28/13	40	111	109	111
12/29/13	41	111	109	
12/30/13	42	110	110	
12/31/13	43	109	109	
1/1/14	44	111	110	
1/2/14	45	110	110	
1/3/14	46	110	110	
1/4/14	47	110	111	
1/5/14	48	109	111	
1/6/14	49	111	109	
1/7/14	50	110	109	
1/8/14	51	110	110	
1/9/14	52	110	109	
1/10/14	53	109	110	
1/11/14	54	111	110	
1/12/14	55	110	109	
1/13/14	56	110	111	
1/14/14	57	111	111	
1/15/14	58	111	110	
1/16/14	59	109	111	110
1/17/14	60	109	110	
1/18/14	61	110	109	
1/19/14	62	109	110	
1/20/14	63	110	110	

Table B.1.2 Record of Water Bath Temperatures – Individual Tank (Continued)

Water Bath Temperature Record - Individual Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
1/21/14	64	110	110	
1/22/14	65	110	110	
1/23/14	66	110	109	
1/24/14	67	109	111	
1/25/14	68	111	110	
1/26/14	69	110	110	
1/27/14	70	110	109	
1/28/14	71	110	111	
1/29/14	72	109	110	
1/30/14	73	111	110	110
1/31/14	74	110	110	
2/1/14	75	110	111	
2/2/14	76	111	111	
2/3/14	77	111	109	
2/4/14	78	109	109	
2/5/14	79	109	110	
2/6/14	80	111	111	
2/7/14	81	109	111	
2/8/14	82	109	111	
2/9/14	83	110	110	
2/10/14	84	109	109	
2/11/14	85	110	111	
2/12/14	86	110	110	
2/13/14	87	110	110	
2/14/14	88	109	110	
2/15/14	89	111	109	
2/16/14	90	110	111	
2/17/14	91	110	110	
2/18/14	92	109	110	
2/19/14	93	111	110	
2/20/14	94	110	109	110
2/21/14	95	110	111	
2/22/14	96	110	110	
2/23/14	97	111	110	
2/24/14	98	111	111	

Table B.1.2 Record of Water Bath Temperatures – Individual Tank (Continued)

Water Bath Temperature Record - Individual Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
2/25/14	99	109	111	
2/26/14	100	109	109	
2/27/14	101	110	110	
2/28/14	102	109	109	
3/1/14	103	111	111	
3/2/14	104	110	110	
3/3/14	105	110	110	
3/4/14	106	111	111	
3/5/14	107	111	111	
3/6/14	108	109	109	
3/7/14	109	109	109	
3/8/14	110	110	110	
3/9/14	111	109	109	
3/10/14	112	110	110	
3/11/14	113	110	110	
3/12/14	114	109	109	
3/13/14	115	111	111	
3/14/14	116	111	111	
3/15/14	117	110	110	110
3/16/14	118	109	109	
3/17/14	119	111	111	
3/18/14	120	110	110	
3/19/14	121	110	110	
3/20/14	122	110	110	
3/21/14	123	109	111	
3/22/14	124	111	110	
3/23/14	125	110	110	
3/24/14	126	111	111	
3/25/14	127	111	111	
3/26/14	128	109	109	
3/27/14	129	109	109	
3/28/14	130	110	110	
3/29/14	131	109	109	
3/30/14	132	111	110	
3/31/14	133	110	109	110

Table B.1.2 Record of Water Bath Temperatures – Individual Tank (Continued)

Water Bath Temperature Record - Individual Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
4/1/14	134	110	109	
4/2/14	135	111	110	
4/3/14	136	111	109	
4/4/14	137	109	110	
4/5/14	138	109	110	
4/6/14	139	110	109	
4/7/14	140	109	111	
4/8/14	141	110	111	
4/9/14	142	109	110	
4/10/14	143	109	109	
4/11/14	144	110	111	
4/12/14	145	109	110	
4/13/14	146	110	110	
4/14/14	147	110	110	
4/15/14	148	109	109	
4/16/14	149	111	111	
4/17/14	150	111	110	
4/18/14	151	110	111	
4/19/14	152	111	111	
4/20/14	153	110	109	
4/21/14	154	109	109	109
4/22/14	155	110	110	
4/23/14	156	111	109	
4/24/14	157	111	110	
4/25/14	158	111	109	
4/26/14	159	110	110	
4/27/14	160	109	110	
4/28/14	161	111	110	
4/29/14	162	110	109	
4/30/14	163	110	111	
5/1/14	164	110	110	
5/2/14	165	109	110	110
5/3/14	166	111	109	
5/4/14	167	110	111	
5/5/14	168	110	110	

Table B.1.2 Record of Water Bath Temperatures – Individual Tank (Continued)

Water Bath Temperature Record - Individual Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
5/6/14	169	110	110	
5/7/14	170	109	111	
5/8/14	171	111	111	
5/9/14	172	110	109	
5/10/14	173	110	109	
5/11/14	174	111	111	
5/12/14	175	111	109	
5/13/14	176	109	109	
5/14/14	177	109	109	
5/15/14	178	111	110	
5/16/14	179	110	110	
5/17/14	180	110	110	
5/18/14	181	110	109	
5/19/14	182	109	111	
5/20/14	183	111	110	
5/21/14	184	110	110	110
5/22/14	185	111	109	
5/23/14	186	111	111	
5/24/14	187	109	110	
5/25/14	188	109	110	
5/26/14	189	110	111	
5/27/14	190	109	111	
5/28/14	191	110	109	
5/29/14	192	109	109	
5/30/14	193	110	111	
5/31/14	194	110	109	
6/1/14	195	110	110	
6/2/14	196	109	111	
6/3/14	197	111	110	
6/4/14	198	110	109	
6/5/14	199	110	110	
6/6/14	200	109	111	
6/7/14	201	111	111	
6/8/14	202	110	111	
6/9/14	203	110	110	

Table B.1.2 Record of Water Bath Temperatures – Individual Tank (Continued)

Water Bath Temperature Record - Individual Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
6/10/14	204	111	109	
6/11/14	205	111	111	
6/12/14	206	109	110	
6/13/14	207	109	110	
6/14/14	208	111	110	111
6/15/14	209	109	109	
6/16/14	210	109	111	
6/17/14	211	110	110	
6/18/14	212	109	110	
6/19/14	213	110	110	
6/20/14	214	110	109	
6/21/14	215	110	111	
6/22/14	216	109	110	
6/23/14	217	111	110	
6/24/14	218	110	111	
6/25/14	219	111	110	
6/26/14	220	111	110	
6/27/14	221	109	110	
6/28/14	222	109	109	
6/29/14	223	110	111	
6/30/14	224	109	111	
7/1/14	225	111	110	111
7/2/14	226	110	111	
7/3/14	227	110	111	
7/4/14	228	111	109	
7/5/14	229	111	109	
7/6/14	230	109	110	
7/7/14	231	109	109	
7/8/14	232	110	111	
7/9/14	233	109	110	
7/10/14	234	111	110	
7/11/14	235	111	111	
7/12/14	236	109	111	
7/13/14	237	109	109	
7/14/14	238	110	109	

Table B.1.2 Record of Water Bath Temperatures – Individual Tank (Continued)

Water Bath Temperature Record - Individual Reactor Set (Continued)				
Date	Days Since Start	AM [^{0}F]	PM [^{0}F]	Manual Reading [^{0}F]
7/15/14	239	109	110	
7/16/14	240	110	109	
7/17/14	241	110	110	
7/18/14	242	109	109	
7/19/14	243	111	109	111
7/20/14	244	111	110	
7/21/14	245	110	109	
7/22/14	246	109	110	
7/23/14	247	111	110	
7/24/14	248	110	110	
7/25/14	249	110	109	
7/26/14	250	111	111	
7/27/14	251	110	110	
7/28/14	252	109	110	
7/29/14	253	110	110	
7/30/14	254	111	109	
7/31/14	255	111	111	
8/1/14	256	111	110	
8/2/14	257	110	110	
8/3/14	258	109	111	
8/4/14	259	111	111	
8/5/14	260	110	109	110
8/6/14	261	110	110	
8/7/14	262	110	109	110

B.2 Gas Volume (Methane) Readings from Gas Totalizer

Gas produced from the composite bioreactor set and each readily, and moderately degradable reactors were collected using an automated gas flow meter (Sierra Instruments model MicroTrak 101) capable of providing instantaneous methane flow rate in standard cubic centimeters per seconds (sccm). Figure B.2.1 through B.2.3 illustrate daily gas flow reported by the gas flow meter, and normalized per pound of waste for the composite, readily, and moderately degradable bioreactor sets, respectively to obtain daily gas production. Tables B.2.1 through B.2.3 tabulate the data recorded on a daily basis, at minimum, by gas flow meter for the respective composite, readily, and moderately degradable bioreactor sets.

Each of the gas meters was connected to a data collection hub via USB on a monthly basis to download daily gas production rates to a data acquisition computer. The required sensitivity range of the gas flow meter for this experiment was obtained by reviewing experimental results from Lifrieri (2010) who tabulated the gas generation rate of the bioreactor system on a 10 day basis. Generally, sensitivity was set between 0 to 30 sccm for composite and readily reactor sets, and 0 to 10 sccm for the moderately degradable set.

For tabulated records of gas production, the column titled " % of theoretical total" was based on a calculated theoretical total gas production of 6.23, 9.04, and 8.43 cubic feet per pound waste for composite, readily, and moderately degradable bioreactor sets, respectively.

It was assumed that methane comprised 55% of the total gas; therefore theoretical methane gas production of 3.43, 4.97, and 4.64 cubic feet per pound waste were used to assess percent of total theoretical for the purpose of evaluating the cumulative production of methane gas from flow meters. Calculations for theoretical total gas quantity were conducted using the lambda method as modified by Lifrieri and detailed in Chapter 3.

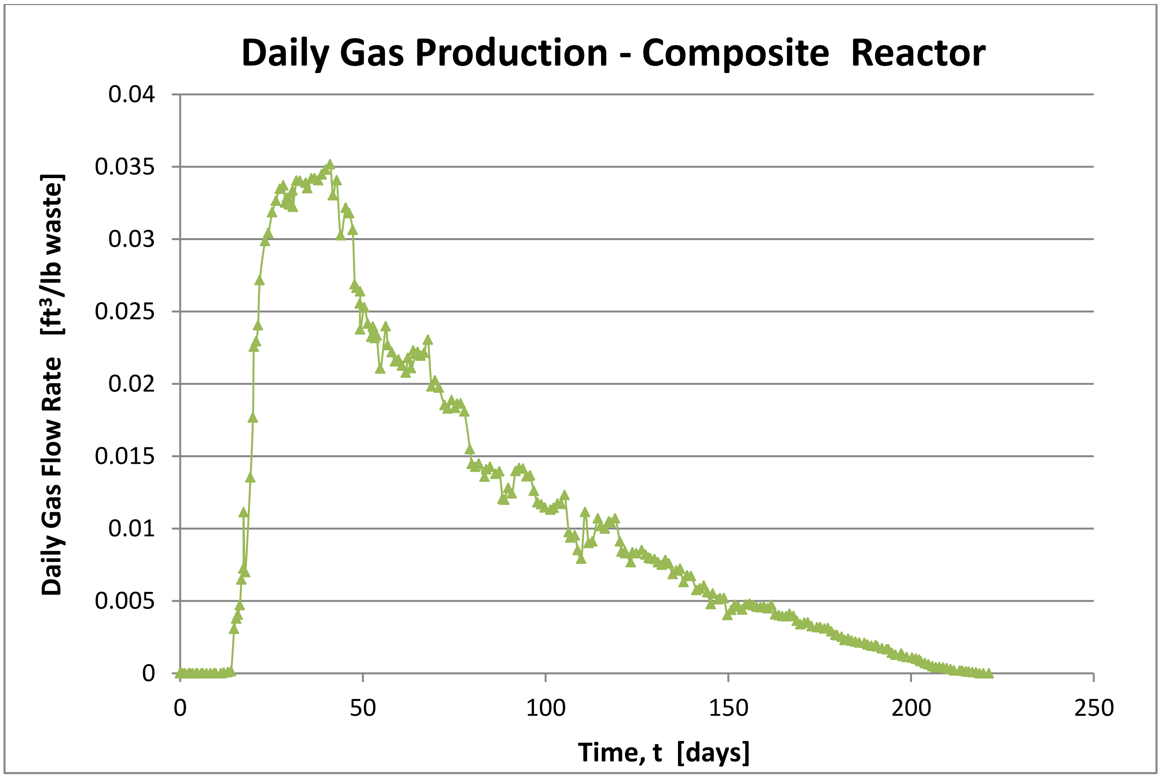

Figure B.2.1 Daily Methane Gas Flow Rate from Meters – Composite Bioreactors

It is comment that the weight of dry weight of waste remaining in bioreactors changes with respect to time as select bioreactors were removed for sampling and testing. The weight of waste removed for each bioreactor is based on the commissioning records provided in Appendix A.

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
11/18/13	13:00	0	0.00	27.32	0.00	0.000	3.40	0%
11/18/13	20:00	0	0.00	27.32	0.00	0.000	3.40	0%
11/19/13	8:00	1	0.00	27.32	0.00	0.000	3.40	0%
11/19/13	21:00	1	0.00	27.32	0.00	0.000	3.40	0%
11/20/13	21:00	2	0.00	27.32	0.00	0.000	3.40	0%
11/21/13	6:00	3	0.00	27.32	0.00	0.000	3.40	0%
11/21/13	21:00	3	0.00	27.32	0.00	0.000	3.40	0%
11/22/13	22:00	4	0.00	27.32	0.00	0.000	3.40	0%
11/23/13	8:00	5	0.00	27.32	0.00	0.000	3.40	0%
11/24/13	8:00	6	0.00	27.32	0.00	0.000	3.40	0%
11/24/13	19:00	6	0.00	27.32	0.00	0.000	3.40	0%
11/25/13	18:00	7	0.00	27.32	0.00	0.000	3.40	0%
11/26/13	20:00	8	0.00	27.32	0.00	0.000	3.40	0%
11/27/13	19:00	9	0.00	27.32	0.00	0.000	3.40	0%
11/28/13	8:00	10	0.00	27.32	0.00	0.000	3.40	0%
11/29/13	18:00	11	0.00	27.32	0.00	0.000	3.40	0%
11/30/13	12:00	12	0.02	27.32	0.00	0.000	3.40	0%
12/1/13	16:00	13	0.04	27.32	0.00	0.000	3.40	0%
12/2/13	12:00	14	0.08	27.32	0.00	0.000	3.40	0%
12/3/13	8:00	15	1.65	27.32	0.06	0.003	3.40	0%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
12/3/13	21:00	15	2.03	27.32	0.07	0.004	3.39	0%
12/4/13	8:00	16	2.18	27.32	0.08	0.004	3.39	0%
12/4/13	21:00	16	2.53	27.32	0.09	0.005	3.39	0%
12/5/13	8:00	17	3.48	27.32	0.13	0.006	3.39	0%
12/5/13	21:00	17	3.89	27.32	0.14	0.007	3.38	0%
12/5/13	21:15	17	5.98	27.32	0.22	0.011	3.38	0%
12/6/13	8:00	18	3.75	27.32	0.14	0.007	3.38	1%
12/7/13	19:00	19	7.27	27.32	0.27	0.014	3.36	1%
12/8/13	11:00	20	9.49	27.32	0.35	0.018	3.35	1%
12/8/13	17:00	20	12.12	27.32	0.44	0.023	3.34	2%
12/9/13	8:00	21	12.32	27.32	0.45	0.023	3.33	2%
12/9/13	21:00	21	12.92	27.32	0.47	0.024	3.32	2%
12/10/13	8:00	22	14.59	27.32	0.53	0.027	3.30	3%
12/11/13	19:00	23	16.05	27.32	0.59	0.030	3.26	4%
12/12/13	16:00	24	16.34	27.32	0.60	0.030	3.23	5%
12/13/13	18:00	25	17.12	27.32	0.63	0.032	3.20	6%
12/14/13	18:00	26	17.55	27.32	0.64	0.033	3.17	7%
12/15/13	19:00	27	17.98	27.32	0.66	0.033	3.13	8%
12/16/13	19:00	28	18.12	27.32	0.66	0.034	3.10	9%
12/17/13	8:00	29	17.47	27.32	0.64	0.033	3.08	9%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
12/17/13	19:00	29	17.64	27.32	0.65	0.033	3.06	10%
12/18/13	8:00	30	17.54	27.32	0.64	0.033	3.05	10%
12/18/13	8:00	30	17.40	27.32	0.64	0.032	3.05	10%
12/19/13	7:00	31	17.92	27.32	0.66	0.033	3.01	11%
12/19/13	9:00	31	17.32	27.32	0.63	0.032	3.01	11%
12/20/13	9:00	32	18.29	27.32	0.67	0.034	2.98	12%
12/21/13	8:00	33	18.28	27.32	0.67	0.034	2.95	13%
12/22/13	21:00	34	18.21	27.32	0.67	0.034	2.89	15%
12/23/13	8:00	35	18.01	27.32	0.66	0.034	2.88	15%
12/24/13	12:00	36	18.37	27.32	0.67	0.034	2.84	17%
12/25/13	8:00	37	18.38	27.32	0.67	0.034	2.81	17%
12/26/13	7:00	38	18.31	27.32	0.67	0.034	2.78	18%
12/27/13	8:00	39	18.52	27.32	0.68	0.034	2.74	19%
12/28/13	8:00	40	18.70	27.32	0.68	0.035	2.71	20%
12/29/13	14:00	41	18.90	27.32	0.69	0.035	2.66	22%
12/30/13	9:00	42	17.75	27.32	0.65	0.033	2.64	22%
12/31/13	9:00	43	18.30	27.32	0.67	0.034	2.60	23%
1/1/14	11:00	44	16.25	27.32	0.59	0.030	2.57	24%
1/2/14	20:00	45	17.28	27.32	0.63	0.032	2.52	26%
1/3/14	19:00	46	17.08	27.32	0.63	0.032	2.49	27%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
1/4/14	18:00	47	16.46	27.32	0.60	0.031	2.46	27%
1/5/14	8:00	48	14.44	27.32	0.53	0.027	2.45	28%
1/5/14	20:00	48	14.31	27.32	0.52	0.027	2.44	28%
1/6/14	20:00	49	14.17	27.32	0.52	0.026	2.41	29%
1/6/14	18:00	49	13.72	27.32	0.50	0.026	2.41	29%
1/6/14	20:00	49	12.76	27.32	0.47	0.024	2.41	29%
1/7/14	22:00	50	12.73	25.61	0.50	0.025	2.38	30%
1/8/14	21:00	51	12.17	25.61	0.48	0.024	2.36	31%
1/9/14	20:00	52	11.71	25.61	0.46	0.023	2.34	31%
1/10/14	8:00	53	12.06	25.61	0.47	0.024	2.32	32%
1/10/14	20:00	53	11.66	25.61	0.46	0.023	2.31	32%
1/11/14	8:00	54	11.75	25.61	0.46	0.023	2.30	32%
1/12/14	8:00	55	10.61	25.61	0.41	0.021	2.28	33%
1/13/14	20:00	56	12.08	25.61	0.47	0.024	2.24	34%
1/14/14	8:00	57	11.42	25.61	0.45	0.023	2.23	34%
1/15/14	11:00	58	11.17	25.61	0.44	0.022	2.21	35%
1/16/14	8:00	59	10.85	25.61	0.42	0.022	2.19	36%
1/17/14	8:00	60	10.92	25.61	0.43	0.022	2.17	36%
1/18/14	7:00	61	10.71	25.61	0.42	0.021	2.15	37%
1/19/14	8:00	62	10.46	25.61	0.41	0.021	2.13	37%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
1/19/14	20:00	62	10.23	23.89	0.43	0.022	2.11	38%
1/20/14	18:00	63	9.90	23.89	0.41	0.021	2.10	38%
1/21/14	21:00	64	10.37	23.89	0.43	0.022	2.07	39%
1/21/14	8:00	64	10.47	23.89	0.44	0.022	2.08	39%
1/22/14	14:00	65	10.44	23.89	0.44	0.022	2.05	40%
1/23/14	8:00	66	10.31	23.89	0.43	0.022	2.04	40%
1/24/14	8:00	67	10.41	23.89	0.44	0.022	2.02	41%
1/25/14	8:00	68	10.83	23.89	0.45	0.023	1.99	41%
1/26/14	8:00	69	9.31	23.89	0.39	0.020	1.97	42%
1/27/14	8:00	70	9.51	23.89	0.40	0.020	1.95	43%
1/28/14	8:00	71	9.27	23.89	0.39	0.020	1.93	43%
1/29/14	21:00	72	8.71	23.89	0.36	0.019	1.90	44%
1/30/14	20:00	73	8.60	23.89	0.36	0.018	1.89	44%
1/31/14	20:00	74	8.87	23.89	0.37	0.019	1.87	45%
2/1/14	19:00	75	8.61	23.89	0.36	0.018	1.85	46%
2/2/14	9:00	76	8.75	23.89	0.37	0.019	1.84	46%
2/3/14	8:00	77	8.76	23.89	0.37	0.019	1.82	46%
2/4/14	8:00	78	8.51	23.89	0.36	0.018	1.80	47%
2/5/14	21:00	79	7.27	23.89	0.30	0.015	1.78	48%
2/6/14	8:00	80	6.80	23.89	0.28	0.014	1.77	48%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter									
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
2/7/14	8:00	81	6.70	23.89	0.28	0.014	1.76	48%
2/8/14	7:30	82	6.81	23.89	0.28	0.014	1.74	49%
2/9/14	21:00	83	6.38	23.89	0.27	0.014	1.72	49%
2/10/14	8:00	84	6.62	23.89	0.28	0.014	1.72	49%
2/11/14	8:00	85	6.70	23.89	0.28	0.014	1.70	50%
2/12/14	21:00	86	6.48	23.89	0.27	0.014	1.68	51%
2/13/14	21:30	87	6.56	23.89	0.27	0.014	1.67	51%
2/14/14	18:30	88	5.67	23.89	0.24	0.012	1.66	51%
2/15/14	6:00	89	5.63	23.89	0.24	0.012	1.65	51%
2/16/14	8:00	90	6.02	23.89	0.25	0.013	1.64	52%
2/17/14	8:00	91	5.84	23.89	0.24	0.012	1.62	52%
2/18/14	8:00	92	5.88	21.38	0.27	0.014	1.61	53%
2/19/14	8:00	93	5.96	21.38	0.28	0.014	1.60	53%
2/20/14	8:00	94	5.94	21.38	0.28	0.014	1.58	53%
2/21/14	8:00	95	5.72	21.38	0.27	0.014	1.57	54%
2/22/14	8:00	96	5.74	21.38	0.27	0.014	1.56	54%
2/23/14	8:00	97	5.30	21.38	0.25	0.013	1.54	55%
2/24/14	8:00	98	4.96	21.38	0.23	0.012	1.53	55%
2/25/14	8:00	99	4.91	21.38	0.23	0.012	1.52	55%
2/26/14	8:00	100	4.81	21.38	0.23	0.011	1.51	56%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
2/27/14	21:00	101	4.75	21.38	0.22	0.011	1.49	56%
2/28/14	18:00	102	4.81	21.38	0.22	0.011	1.48	56%
3/1/14	20:00	103	4.93	21.38	0.23	0.012	1.47	57%
3/2/14	19:00	104	4.92	21.38	0.23	0.012	1.46	57%
3/3/14	18:00	105	5.18	21.38	0.24	0.012	1.44	57%
3/4/14	21:00	106	4.10	21.38	0.19	0.010	1.43	58%
3/5/14	8:00	107	3.94	21.38	0.18	0.009	1.43	58%
3/6/14	14:00	108	4.01	21.38	0.19	0.010	1.42	58%
3/7/14	8:00	109	3.58	21.38	0.17	0.009	1.41	58%
3/8/14	8:00	110	3.33	21.38	0.16	0.008	1.40	59%
3/9/14	8:00	111	4.69	21.38	0.22	0.011	1.39	59%
3/10/14	8:00	112	3.79	21.38	0.18	0.009	1.38	59%
3/11/14	10:00	113	3.83	21.38	0.18	0.009	1.37	60%
3/12/14	20:00	114	4.50	21.38	0.21	0.011	1.36	60%
3/13/14	16:00	115	4.27	21.38	0.20	0.010	1.35	60%
3/14/14	18:00	116	4.20	21.38	0.20	0.010	1.34	61%
3/15/14	21:00	117	4.41	21.38	0.21	0.010	1.33	61%
3/16/14	8:00	118	4.38	21.38	0.20	0.010	1.32	61%
3/17/14	14:00	119	4.50	21.38	0.21	0.011	1.31	61%
3/18/14	21:00	120	3.83	21.38	0.18	0.009	1.30	62%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
3/19/14	8:00	121	3.53	21.38	0.17	0.008	1.29	62%
3/20/14	8:00	122	3.49	21.38	0.16	0.008	1.28	62%
3/20/14	7:30	122	3.26	19.66	0.17	0.008	1.28	62%
3/21/14	21:00	123	2.97	19.66	0.15	0.008	1.27	63%
3/22/14	8:00	124	3.23	19.66	0.16	0.008	1.27	63%
3/23/14	8:00	125	3.20	19.66	0.16	0.008	1.26	63%
3/24/14	21:00	126	3.29	19.66	0.17	0.009	1.25	63%
3/25/14	21:30	127	3.17	19.66	0.16	0.008	1.24	64%
3/26/14	18:30	128	3.09	19.66	0.16	0.008	1.23	64%
3/27/14	6:00	129	3.07	19.66	0.16	0.008	1.23	64%
3/28/14	8:00	130	3.05	19.66	0.16	0.008	1.22	64%
3/29/14	8:00	131	2.97	19.66	0.15	0.008	1.21	64%
3/30/14	8:00	132	2.90	19.66	0.15	0.008	1.20	65%
3/31/14	8:00	133	3.03	19.66	0.15	0.008	1.20	65%
4/1/14	8:00	134	2.93	19.66	0.15	0.008	1.19	65%
4/2/14	8:00	135	2.65	19.66	0.13	0.007	1.18	65%
4/3/14	8:00	136	2.75	19.66	0.14	0.007	1.18	65%
4/4/14	8:00	137	2.80	19.66	0.14	0.007	1.17	66%
4/5/14	8:00	138	2.43	19.66	0.12	0.006	1.16	66%
4/6/14	8:00	139	2.62	19.66	0.13	0.007	1.16	66%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
4/7/14	8:00	140	2.60	19.66	0.13	0.007	1.15	66%
4/8/14	21:00	141	2.23	19.66	0.11	0.006	1.14	66%
4/9/14	18:00	142	2.26	19.66	0.12	0.006	1.13	67%
4/10/14	20:00	143	2.34	19.66	0.12	0.006	1.13	67%
4/11/14	19:00	144	2.16	19.66	0.11	0.006	1.12	67%
4/12/14	18:00	145	1.85	19.66	0.09	0.005	1.12	67%
4/13/14	8:00	146	2.13	19.66	0.11	0.006	1.11	67%
4/14/14	19:00	147	1.98	19.66	0.10	0.005	1.11	67%
4/15/14	8:00	148	2.01	19.66	0.10	0.005	1.10	68%
4/16/14	8:00	149	2.01	19.66	0.10	0.005	1.10	68%
4/17/14	7:00	150	1.55	19.66	0.08	0.004	1.10	68%
4/18/14	9:00	151	1.69	19.66	0.09	0.004	1.09	68%
4/19/14	9:00	152	1.83	19.66	0.09	0.005	1.09	68%
4/20/14	8:00	153	1.78	19.66	0.09	0.005	1.08	68%
4/21/14	8:00	154	1.70	19.66	0.09	0.004	1.08	68%
4/22/14	8:00	155	1.84	19.66	0.09	0.005	1.07	68%
4/23/14	8:00	156	1.85	19.66	0.09	0.005	1.07	69%
4/24/14	8:00	157	1.82	19.66	0.09	0.005	1.06	69%
4/25/14	8:00	158	1.78	19.66	0.09	0.005	1.06	69%
4/26/14	8:00	159	1.76	19.66	0.09	0.005	1.05	69%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
4/27/14	8:00	160	1.80	19.66	0.09	0.005	1.05	69%
4/28/14	8:00	161	1.73	19.66	0.09	0.004	1.04	69%
4/29/14	8:00	162	1.83	19.66	0.09	0.005	1.04	69%
4/30/14	8:00	163	1.57	19.66	0.08	0.004	1.04	70%
5/1/14	8:00	164	1.56	19.66	0.08	0.004	1.03	70%
5/2/14	8:00	165	1.53	19.66	0.08	0.004	1.03	70%
5/3/14	8:00	166	1.52	19.66	0.08	0.004	1.02	70%
5/4/14	8:00	167	1.59	19.66	0.08	0.004	1.02	70%
5/5/14	8:00	168	1.53	19.66	0.08	0.004	1.02	70%
5/6/14	8:00	169	1.40	19.66	0.07	0.004	1.01	70%
5/7/14	8:00	170	1.31	19.66	0.07	0.003	1.01	70%
5/8/14	8:00	171	1.35	19.66	0.07	0.003	1.01	70%
5/9/14	8:00	172	1.36	19.66	0.07	0.004	1.00	71%
5/10/14	8:00	173	1.26	19.66	0.06	0.003	1.00	71%
5/11/14	21:00	174	1.23	19.66	0.06	0.003	0.99	71%
5/12/14	18:00	175	1.23	19.66	0.06	0.003	0.99	71%
5/13/14	20:00	176	1.20	19.66	0.06	0.003	0.99	71%
5/14/14	19:00	177	1.20	19.66	0.06	0.003	0.98	71%
5/15/14	18:00	178	1.12	19.66	0.06	0.003	0.98	71%
5/16/14	21:00	179	1.02	19.66	0.05	0.003	0.98	71%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter									
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
5/17/14	8:00	180	1.02	19.66	0.05	0.003	0.98	71%
5/18/14	14:00	181	0.98	19.66	0.05	0.003	0.97	71%
5/19/14	8:00	182	0.89	19.66	0.05	0.002	0.97	71%
5/20/14	8:00	183	0.93	19.66	0.05	0.002	0.97	71%
5/21/14	8:00	184	0.87	19.66	0.04	0.002	0.97	72%
5/22/14	8:00	185	0.84	19.66	0.04	0.002	0.97	72%
5/23/14	10:00	186	0.82	19.66	0.04	0.002	0.96	72%
5/24/14	20:00	187	0.81	19.66	0.04	0.002	0.96	72%
5/25/14	16:00	188	0.76	19.66	0.04	0.002	0.96	72%
5/26/14	18:00	189	0.74	19.66	0.04	0.002	0.96	72%
5/27/14	21:00	190	0.69	17.94	0.04	0.002	0.95	72%
5/28/14	8:00	191	0.65	17.94	0.04	0.002	0.95	72%
5/29/14	14:00	192	0.61	17.94	0.03	0.002	0.95	72%
5/30/14	21:00	193	0.58	17.94	0.03	0.002	0.95	72%
5/31/14	8:00	194	0.58	17.94	0.03	0.002	0.95	72%
6/1/14	8:00	195	0.50	17.94	0.03	0.001	0.95	72%
6/2/14	7:30	196	0.45	17.94	0.03	0.001	0.95	72%
6/3/14	21:00	197	0.48	17.94	0.03	0.001	0.94	72%
6/4/14	8:00	198	0.42	17.94	0.02	0.001	0.94	72%
6/5/14	8:00	199	0.40	17.94	0.02	0.001	0.94	72%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
6/6/14	21:00	200	0.38	17.94	0.02	0.001	0.94	72%
6/7/14	21:30	201	0.36	17.94	0.02	0.001	0.94	72%
6/8/14	18:30	202	0.33	17.94	0.02	0.001	0.94	72%
6/9/14	6:00	203	0.30	17.94	0.02	0.001	0.94	72%
6/10/14	8:00	204	0.25	17.94	0.01	0.001	0.94	72%
6/11/14	8:00	205	0.22	17.94	0.01	0.001	0.94	72%
6/12/14	8:00	206	0.17	17.94	0.01	0.000	0.94	72%
6/13/14	8:00	207	0.15	17.94	0.01	0.000	0.94	72%
6/14/14	8:00	208	0.16	17.94	0.01	0.000	0.94	72%
6/15/14	8:00	209	0.14	17.94	0.01	0.000	0.94	72%
6/16/14	8:00	210	0.13	17.94	0.01	0.000	0.93	72%
6/17/14	8:00	211	0.10	17.94	0.01	0.000	0.93	73%
6/18/14	7:30	212	0.07	17.94	0.00	0.000	0.93	73%
6/19/14	21:00	213	0.07	17.94	0.00	0.000	0.93	73%
6/20/14	14:00	214	0.06	17.94	0.00	0.000	0.93	73%
6/21/14	14:00	215	0.04	17.94	0.00	0.000	0.93	73%
6/22/14	8:00	216	0.03	17.94	0.00	0.000	0.93	73%
6/23/14	8:00	217	0.03	17.94	0.00	0.000	0.93	73%
6/24/14	8:00	218	0.02	17.94	0.00	0.000	0.93	73%
6/25/14	8:00	219	0.00	17.94	0.00	0.000	0.93	73%

Table B.2.1 Record of Gas Flow Readings – Composite Bioreactors (continued)

Gas Flow Meter Readings - Composite Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
6/26/14	10:00	220	0.00	17.94	0.00	0.000	0.93	73%
6/27/14	20:00	221	0.00	17.94	0.00	0.000	0.93	73%

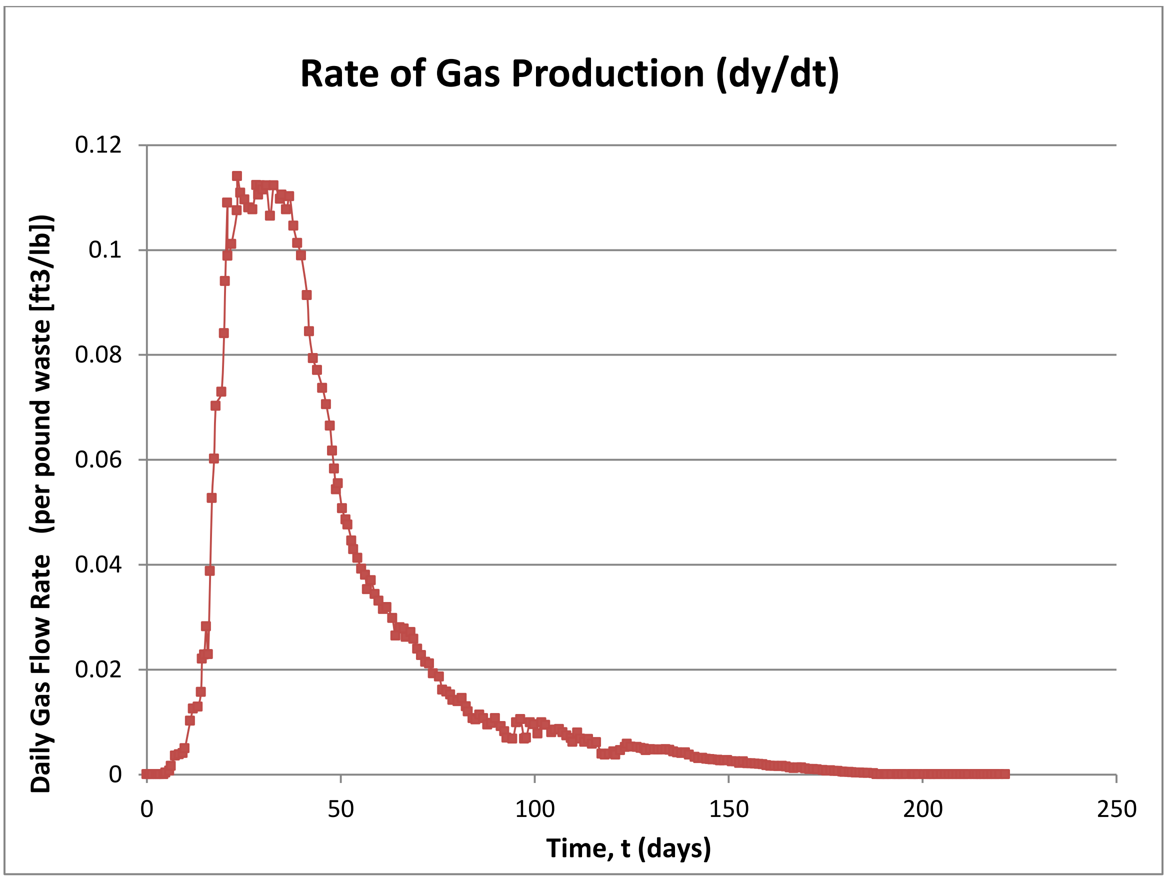

Figure B.2.2 Daily Methane Gas Flow Rate from Meters – Readily Deg. Bioreactors

Table B.2.2 Record of Gas Flow Readings – Readily Degradable Bioreactors

Gas Flow Meter Readings – Readily Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
11/18/13	13:00	0	0.00	11.48	0.00	0.000	4.97	0%
11/18/13	20:00	0	0.00	11.48	0.00	0.000	4.97	0%
11/19/13	8:00	1	0.00	11.48	0.00	0.000	4.97	0%
11/19/13	21:00	1	0.00	11.48	0.00	0.000	4.97	0%
11/20/13	21:00	2	0.00	11.48	0.00	0.000	4.97	0%
11/21/13	8:00	3	0.00	11.48	0.00	0.000	4.97	0%
11/21/13	21:00	3	0.00	11.48	0.00	0.000	4.97	0%
11/22/13	22:00	4	0.00	11.48	0.00	0.000	4.97	0%
11/23/13	8:00	5	0.08	11.48	0.01	0.000	4.97	0%
11/24/13	8:00	6	0.16	11.48	0.01	0.001	4.97	0%
11/24/13	19:00	6	0.37	11.48	0.03	0.002	4.97	0%
11/25/13	20:00	7	0.80	11.48	0.07	0.004	4.97	0%
11/26/13	20:00	8	0.86	11.48	0.07	0.004	4.96	0%
11/27/13	19:00	9	0.91	11.48	0.08	0.004	4.96	0%
11/28/13	8:00	10	1.12	11.48	0.10	0.005	4.96	0%
11/29/13	18:00	11	2.31	11.48	0.20	0.010	4.94	1%
11/30/13	12:00	12	2.83	11.48	0.25	0.013	4.93	1%
12/1/13	16:00	13	2.91	11.48	0.25	0.013	4.92	1%
12/2/13	12:00	14	3.54	11.48	0.31	0.016	4.90	1%
12/2/13	19:00	14	4.97	11.48	0.43	0.022	4.90	1%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
12/3/13	8:00	15	5.15	11.48	0.45	0.023	4.89	2%
12/3/13	21:00	15	6.37	11.48	0.55	0.028	4.87	2%
12/4/13	8:00	16	5.17	11.48	0.45	0.023	4.86	2%
12/4/13	21:00	16	8.75	11.48	0.76	0.039	4.84	3%
12/5/13	8:00	17	11.89	11.48	1.04	0.053	4.81	3%
12/5/13	21:00	17	13.58	11.48	1.18	0.060	4.78	4%
12/6/13	8:00	18	15.86	11.48	1.38	0.070	4.75	4%
12/7/13	19:00	19	16.46	11.48	1.43	0.073	4.64	7%
12/8/13	11:00	20	18.98	11.48	1.65	0.084	4.59	8%
12/8/13	18:00	20	21.23	11.48	1.85	0.094	4.56	8%
12/9/13	8:00	21	24.60	11.48	2.14	0.109	4.50	10%
12/9/13	9:00	21	22.32	11.48	1.94	0.099	4.49	10%
12/10/13	8:00	22	22.83	11.48	1.99	0.101	4.40	12%
12/11/13	19:00	23	24.27	11.48	2.11	0.108	4.24	15%
12/11/13	20:00	23	25.74	11.48	2.24	0.114	4.23	15%
12/12/13	16:00	24	25.02	11.48	2.18	0.111	4.14	17%
12/13/13	18:00	25	24.74	11.48	2.16	0.110	4.02	19%
12/14/13	18:00	26	24.39	11.48	2.12	0.108	3.91	21%
12/15/13	19:00	27	24.31	11.48	2.12	0.108	3.80	24%
12/16/13	19:00	28	25.36	11.48	2.21	0.112	3.69	26%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
12/17/13	8:00	29	24.95	11.48	2.17	0.111	3.63	27%
12/17/13	20:00	29	25.35	11.48	2.21	0.112	3.57	28%
12/18/13	8:00	30	25.17	11.48	2.19	0.111	3.52	29%
12/19/13	8:00	31	25.35	11.48	2.21	0.112	3.41	31%
12/20/13	8:00	32	24.03	11.48	2.09	0.106	3.30	34%
12/21/13	7:00	33	25.35	11.48	2.21	0.112	3.19	36%
12/22/13	21:00	34	24.77	11.48	2.16	0.110	3.02	39%
12/23/13	8:00	35	24.95	11.48	2.17	0.111	2.97	40%
12/24/13	12:00	36	24.31	11.48	2.12	0.108	2.84	43%
12/25/13	8:00	37	24.88	11.48	2.17	0.110	2.75	45%
12/26/13	8:00	38	23.61	11.48	2.06	0.105	2.65	47%
12/27/13	8:00	39	22.87	11.48	1.99	0.101	2.54	49%
12/28/13	8:00	40	22.33	11.48	1.95	0.099	2.45	51%
12/29/13	21:00	41	20.62	11.48	1.80	0.091	2.30	54%
12/30/13	9:00	42	19.06	11.48	1.66	0.084	2.26	54%
12/31/13	9:00	43	17.91	11.48	1.56	0.079	2.18	56%
1/1/14	11:00	44	17.40	11.48	1.52	0.077	2.10	58%
1/2/14	20:00	45	16.63	11.48	1.45	0.074	2.00	60%
1/3/14	19:00	46	15.92	11.48	1.39	0.071	1.93	61%
1/4/14	18:00	47	15.00	11.48	1.31	0.066	1.87	62%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
1/5/14	8:00	48	13.93	11.48	1.21	0.062	1.83	63%
1/5/14	20:00	48	13.15	11.48	1.15	0.058	1.80	64%
1/6/14	8:00	49	12.26	11.48	1.07	0.054	1.77	64%
1/6/14	20:00	49	12.52	11.48	1.09	0.055	1.75	65%
1/7/14	21:00	50	11.45	11.48	1.00	0.051	1.69	66%
1/8/14	20:00	51	10.96	11.48	0.95	0.049	1.65	67%
1/9/14	8:00	52	10.74	11.48	0.94	0.048	1.62	67%
1/10/14	8:00	53	10.06	11.48	0.88	0.045	1.58	68%
1/10/14	20:00	53	9.68	11.48	0.84	0.043	1.56	69%
1/11/14	20:00	54	9.32	11.48	0.81	0.041	1.52	69%
1/12/14	20:00	55	8.84	11.48	0.77	0.039	1.48	70%
1/13/14	20:00	56	8.58	11.48	0.75	0.038	1.44	71%
1/14/14	8:00	57	7.97	11.48	0.69	0.035	1.42	71%
1/15/14	8:00	58	8.35	11.48	0.73	0.037	1.38	72%
1/16/14	8:00	59	7.76	11.48	0.68	0.034	1.35	73%
1/17/14	8:00	60	7.47	11.48	0.65	0.033	1.32	74%
1/18/14	11:00	61	7.11	11.48	0.62	0.031	1.28	74%
1/19/14	10:00	62	7.19	11.48	0.63	0.032	1.25	75%
1/20/14	20:00	63	6.73	11.48	0.59	0.030	1.21	76%
1/21/14	16:00	64	5.97	11.48	0.52	0.026	1.19	76%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter									
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
1/22/14	18:00	65	6.33	11.48	0.55	0.028	1.16	77%
1/23/14	21:00	66	6.27	11.48	0.55	0.028	1.13	77%
1/24/14	8:00	67	5.91	11.48	0.51	0.026	1.11	78%
1/25/14	14:00	68	6.12	11.48	0.53	0.027	1.08	78%
1/26/14	8:00	69	5.83	11.48	0.51	0.026	1.06	79%
1/27/14	8:00	70	5.41	11.48	0.47	0.024	1.04	79%
1/28/14	8:00	71	5.13	11.48	0.45	0.023	1.01	80%
1/29/14	8:00	72	4.84	11.48	0.42	0.021	0.99	80%
1/30/14	8:00	73	4.77	11.48	0.42	0.021	0.97	80%
1/31/14	8:00	74	4.35	11.48	0.38	0.019	0.95	81%
2/1/14	21:00	75	4.21	11.48	0.37	0.019	0.92	81%
2/2/14	18:00	76	3.64	11.48	0.32	0.016	0.91	82%
2/3/14	20:00	77	3.56	11.48	0.31	0.016	0.89	82%
2/4/14	19:00	78	3.43	11.48	0.30	0.015	0.88	82%
2/5/14	9:00	79	3.20	11.48	0.28	0.014	0.87	83%
2/6/14	16:00	80	3.14	11.48	0.27	0.014	0.85	83%
2/7/14	18:00	81	3.28	11.48	0.29	0.015	0.84	83%
2/8/14	21:00	82	2.92	11.48	0.25	0.013	0.82	83%
2/9/14	8:00	83	2.71	11.48	0.24	0.012	0.82	84%
2/10/14	14:00	84	2.42	11.48	0.21	0.011	0.80	84%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
2/11/14	8:00	85	2.36	11.48	0.21	0.010	0.79	84%
2/12/14	8:00	86	2.57	11.48	0.22	0.011	0.78	84%
2/13/14	8:00	87	2.42	11.48	0.21	0.011	0.77	84%
2/14/14	8:00	88	2.14	11.48	0.19	0.009	0.76	85%
2/15/14	8:00	89	2.21	11.48	0.19	0.010	0.75	85%
2/16/14	8:00	90	2.42	11.48	0.21	0.011	0.74	85%
2/17/14	21:00	91	2.07	11.48	0.18	0.009	0.73	85%
2/18/14	18:00	92	1.85	11.48	0.16	0.008	0.72	86%
2/19/14	8:00	93	1.58	11.48	0.14	0.007	0.72	86%
2/20/14	20:00	94	1.54	11.48	0.13	0.007	0.71	86%
2/21/14	20:00	95	2.24	11.48	0.20	0.010	0.70	86%
2/22/14	20:00	96	2.38	11.48	0.21	0.011	0.69	86%
2/23/14	20:00	97	1.54	11.48	0.13	0.007	0.68	86%
2/24/14	8:00	98	1.57	11.48	0.14	0.007	0.68	86%
2/25/14	8:00	99	2.24	11.48	0.20	0.010	0.67	87%
2/26/14	8:00	100	2.16	11.48	0.19	0.010	0.66	87%
2/27/14	8:00	101	1.75	11.48	0.15	0.008	0.65	87%
2/28/14	8:00	102	2.23	11.48	0.19	0.010	0.64	87%
3/1/14	8:00	103	2.12	11.48	0.18	0.009	0.63	87%
3/2/14	21:00	104	1.81	11.48	0.16	0.008	0.62	88%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
3/3/14	18:00	105	1.92	11.48	0.17	0.009	0.61	88%
3/4/14	20:00	106	1.95	11.48	0.17	0.009	0.60	88%
3/5/14	19:00	107	1.81	11.48	0.16	0.008	0.59	88%
3/6/14	18:00	108	1.67	11.48	0.15	0.007	0.59	88%
3/7/14	21:00	109	1.56	11.48	0.14	0.007	0.58	88%
3/8/14	8:00	110	1.40	11.48	0.12	0.006	0.57	88%
3/9/14	14:00	111	1.79	11.48	0.16	0.008	0.56	89%
3/10/14	8:00	112	1.53	11.48	0.13	0.007	0.56	89%
3/11/14	8:00	113	1.40	11.48	0.12	0.006	0.55	89%
3/12/14	8:00	114	1.52	11.48	0.13	0.007	0.55	89%
3/13/14	8:00	115	1.31	11.48	0.11	0.006	0.54	89%
3/14/14	10:00	116	1.38	11.48	0.12	0.006	0.53	89%
3/15/14	20:00	117	0.89	11.48	0.08	0.004	0.53	89%
3/16/14	16:00	118	0.85	11.48	0.07	0.004	0.53	89%
3/17/14	18:00	119	0.89	11.48	0.08	0.004	0.52	90%
3/18/14	21:00	120	0.98	11.48	0.09	0.004	0.52	90%
3/19/14	8:00	121	0.85	11.48	0.07	0.004	0.51	90%
3/20/14	14:00	122	1.04	11.48	0.09	0.005	0.51	90%
3/21/14	21:00	123	1.17	11.48	0.10	0.005	0.50	90%
3/22/14	8:00	124	1.31	11.48	0.11	0.006	0.50	90%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
3/23/14	8:00	125	1.19	11.48	0.10	0.005	0.49	90%
3/24/14	21:00	126	1.17	11.48	0.10	0.005	0.49	90%
3/25/14	21:30	127	1.13	11.48	0.10	0.005	0.48	90%
3/26/14	18:30	128	1.11	11.48	0.10	0.005	0.48	90%
3/27/14	6:00	129	1.04	11.48	0.09	0.005	0.47	90%
3/28/14	8:00	130	1.08	11.48	0.09	0.005	0.47	91%
3/29/14	8:00	131	1.07	11.48	0.09	0.005	0.46	91%
3/30/14	8:00	132	1.06	11.48	0.09	0.005	0.46	91%
3/31/14	8:00	133	1.07	11.48	0.09	0.005	0.46	91%
4/1/14	8:00	134	1.08	11.48	0.09	0.005	0.45	91%
4/2/14	8:00	135	1.05	11.48	0.09	0.005	0.45	91%
4/3/14	8:00	136	0.98	11.48	0.09	0.004	0.44	91%
4/4/14	8:00	137	0.94	11.48	0.08	0.004	0.44	91%
4/5/14	8:00	138	0.91	11.48	0.08	0.004	0.43	91%
4/6/14	8:00	139	0.94	11.48	0.08	0.004	0.43	91%
4/7/14	8:00	140	0.84	11.48	0.07	0.004	0.43	91%
4/8/14	21:00	141	0.75	11.48	0.07	0.003	0.42	92%
4/9/14	18:00	142	0.70	11.48	0.06	0.003	0.42	92%
4/10/14	20:00	143	0.71	11.48	0.06	0.003	0.41	92%
4/11/14	19:00	144	0.66	11.48	0.06	0.003	0.41	92%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
4/12/14	18:00	145	0.65	11.48	0.06	0.003	0.41	92%
4/13/14	8:00	146	0.64	11.48	0.06	0.003	0.41	92%
4/14/14	19:00	147	0.62	11.48	0.05	0.003	0.40	92%
4/15/14	8:00	148	0.60	11.48	0.05	0.003	0.40	92%
4/16/14	8:00	149	0.60	11.48	0.05	0.003	0.40	92%
4/17/14	7:00	150	0.61	11.48	0.05	0.003	0.40	92%
4/18/14	9:00	151	0.56	11.48	0.05	0.002	0.39	92%
4/19/14	9:00	152	0.55	11.48	0.05	0.002	0.39	92%
4/20/14	8:00	153	0.49	11.48	0.04	0.002	0.39	92%
4/21/14	8:00	154	0.56	11.48	0.05	0.002	0.39	92%
4/22/14	8:00	155	0.48	11.48	0.04	0.002	0.38	92%
4/23/14	8:00	156	0.47	11.48	0.04	0.002	0.38	92%
4/24/14	8:00	157	0.46	11.48	0.04	0.002	0.38	92%
4/25/14	8:00	158	0.45	11.48	0.04	0.002	0.38	92%
4/26/14	8:00	159	0.43	11.48	0.04	0.002	0.38	92%
4/27/14	8:00	160	0.39	11.48	0.03	0.002	0.37	92%
4/28/14	8:00	161	0.37	11.48	0.03	0.002	0.37	93%
4/29/14	8:00	162	0.37	11.48	0.03	0.002	0.37	93%
4/30/14	8:00	163	0.35	11.48	0.03	0.002	0.37	93%
5/1/14	8:00	164	0.36	11.48	0.03	0.002	0.37	93%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
5/2/14	8:00	165	0.33	11.48	0.03	0.001	0.37	93%
5/3/14	8:00	166	0.30	11.48	0.03	0.001	0.37	93%
5/4/14	8:00	167	0.27	11.48	0.02	0.001	0.36	93%
5/5/14	8:00	168	0.30	11.48	0.03	0.001	0.36	93%
5/6/14	8:00	169	0.29	11.48	0.03	0.001	0.36	93%
5/7/14	8:00	170	0.25	11.48	0.02	0.001	0.36	93%
5/8/14	8:00	171	0.23	11.48	0.02	0.001	0.36	93%
5/9/14	8:00	172	0.22	11.48	0.02	0.001	0.36	93%
5/10/14	8:00	173	0.21	11.48	0.02	0.001	0.36	93%
5/11/14	21:00	174	0.18	11.48	0.02	0.001	0.36	93%
5/12/14	18:00	175	0.16	11.48	0.01	0.001	0.36	93%
5/13/14	20:00	176	0.17	11.48	0.01	0.001	0.35	93%
5/14/14	19:00	177	0.15	11.48	0.01	0.001	0.35	93%
5/15/14	18:00	178	0.14	11.48	0.01	0.001	0.35	93%
5/16/14	21:00	179	0.12	11.48	0.01	0.001	0.35	93%
5/17/14	8:00	180	0.10	11.48	0.01	0.000	0.35	93%
5/18/14	14:00	181	0.10	11.48	0.01	0.000	0.35	93%
5/19/14	8:00	182	0.09	11.48	0.01	0.000	0.35	93%
5/20/14	8:00	183	0.08	11.48	0.01	0.000	0.35	93%
5/21/14	8:00	184	0.08	11.48	0.01	0.000	0.35	93%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter									
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
5/22/14	8:00	185	0.06	11.48	0.01	0.000	0.35	93%
5/23/14	10:00	186	0.06	11.48	0.01	0.000	0.35	93%
5/24/14	20:00	187	0.04	11.48	0.00	0.000	0.35	93%
5/25/14	16:00	188	0.00	11.48	0.00	0.000	0.35	93%
5/26/14	18:00	189	0.00	11.48	0.00	0.000	0.35	93%
5/27/14	21:00	190	0.00	11.48	0.00	0.000	0.35	93%
5/28/14	8:00	191	0.00	11.48	0.00	0.000	0.35	93%
5/29/14	14:00	192	0.00	11.48	0.00	0.000	0.35	93%
5/30/14	21:00	193	0.00	11.48	0.00	0.000	0.35	93%
5/31/14	8:00	194	0.00	11.48	0.00	0.000	0.35	93%
6/1/14	8:00	195	0.00	11.48	0.00	0.000	0.35	93%
6/2/14	7:30	196	0.00	11.48	0.00	0.000	0.35	93%
6/3/14	21:00	197	0.00	11.48	0.00	0.000	0.35	93%
6/4/14	8:00	198	0.00	11.48	0.00	0.000	0.35	93%
6/5/14	8:00	199	0.00	11.48	0.00	0.000	0.35	93%
6/6/14	21:00	200	0.00	11.48	0.00	0.000	0.35	93%
6/7/14	21:30	201	0.00	11.48	0.00	0.000	0.35	93%
6/8/14	18:30	202	0.00	11.48	0.00	0.000	0.35	93%
6/9/14	6:00	203	0.00	11.48	0.00	0.000	0.35	93%
6/10/14	8:00	204	0.00	11.48	0.00	0.000	0.35	93%

Table B.2.2 Record of Gas Flow Readings – Readily Deg. Bioreactors (continued)

Gas Flow Meter Readings – Readily Deg. Flow Meter									
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
6/11/14	8:00	205	0.00	11.48	0.00	0.000	0.35	93%
6/12/14	8:00	206	0.00	11.48	0.00	0.000	0.35	93%
6/13/14	8:00	207	0.00	11.48	0.00	0.000	0.35	93%
6/14/14	8:00	208	0.00	11.48	0.00	0.000	0.35	93%
6/15/14	8:00	209	0.00	11.48	0.00	0.000	0.35	93%
6/16/14	8:00	210	0.00	11.48	0.00	0.000	0.35	93%
6/17/14	8:00	211	0.00	11.48	0.00	0.000	0.35	93%
6/18/14	7:30	212	0.00	11.48	0.00	0.000	0.35	93%
6/19/14	21:00	213	0.00	11.48	0.00	0.000	0.35	93%
6/20/14	14:00	214	0.00	11.48	0.00	0.000	0.35	93%
6/21/14	14:00	215	0.00	11.48	0.00	0.000	0.35	93%
6/22/14	8:00	216	0.00	11.48	0.00	0.000	0.35	93%
6/23/14	8:00	217	0.00	11.48	0.00	0.000	0.35	93%
6/24/14	8:00	218	0.00	11.48	0.00	0.000	0.35	93%
6/25/14	8:00	219	0.00	11.48	0.00	0.000	0.35	93%
6/26/14	10:00	220	0.00	11.48	0.00	0.000	0.35	93%
6/27/14	20:00	221	0.00	11.48	0.00	0.000	0.35	93%

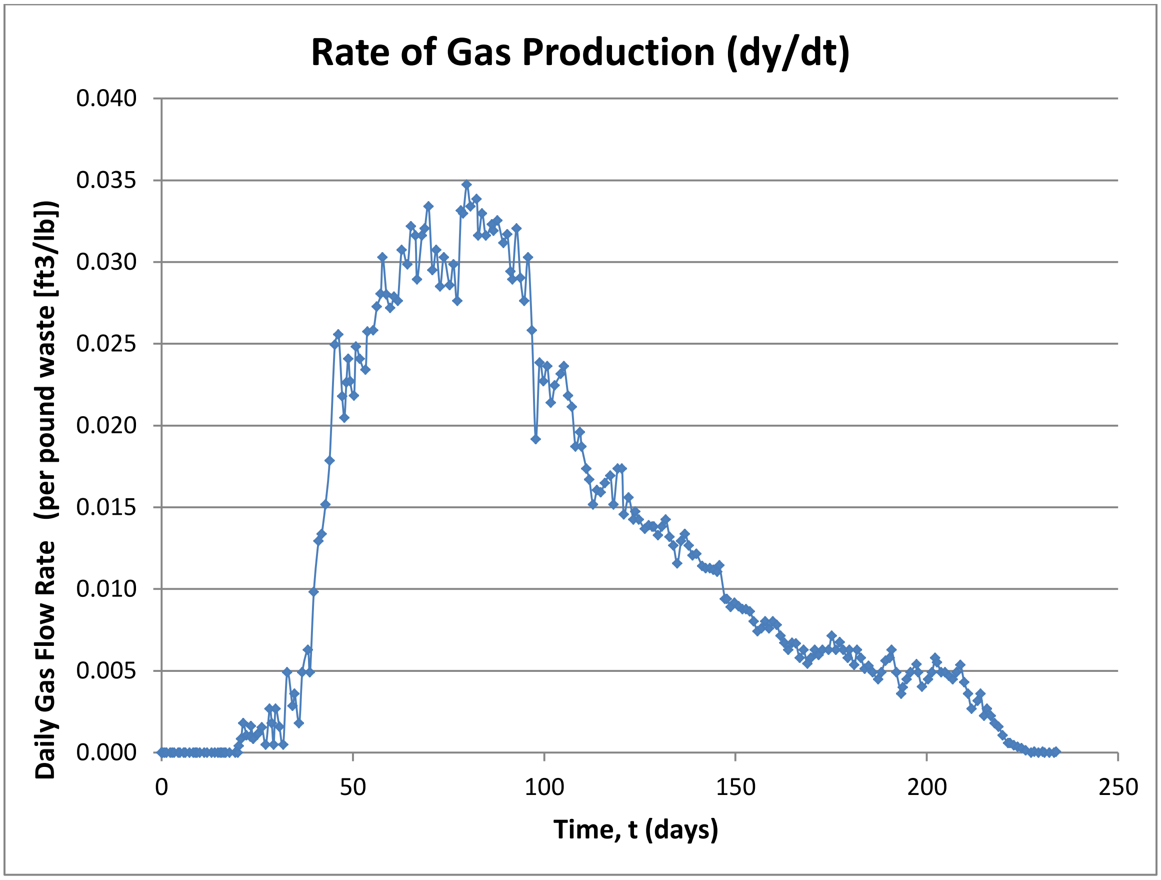

Figure B.2.3 Daily Methane Gas Flow Rate from Meters – Moderately Degradable Bioreactors

Table B.2.3 Record of Gas Flow Readings – Moderately Degradable Bioreactors

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
11/18/13	13:00	0	0.00	11.60		0.000	4.64	0%
11/18/13	20:00	0	0.00	11.60	0.00	0.000	4.64	0%
11/19/13	8:00	1	0.00	11.60	0.00	0.000	4.64	0%
11/19/13	21:00	1	0.00	11.60	0.00	0.000	4.64	0%
11/20/13	21:00	2	0.00	11.60	0.00	0.000	4.64	0%
11/21/13	8:00	3	0.00	11.60	0.00	0.000	4.64	0%
11/21/13	21:00	3	0.00	11.60	0.00	0.000	4.64	0%
11/22/13	22:00	4	0.00	11.60	0.00	0.000	4.64	0%
11/23/13	8:00	5	0.00	11.60	0.00	0.000	4.64	0%
11/24/13	8:00	6	0.00	11.60	0.00	0.000	4.64	0%
11/24/13	19:00	6	0.00	11.60	0.00	0.000	4.64	0%
11/25/13	20:00	7	0.00	11.60	0.00	0.000	4.64	0%
11/26/13	20:00	8	0.00	11.60	0.00	0.000	4.64	0%
11/27/13	19:00	9	0.00	11.60	0.00	0.000	4.64	0%
11/27/13	8:00	9	0.00	11.60	0.00	0.000	4.64	0%
11/27/13	18:00	9	0.00	11.60	0.00	0.000	4.64	0%
11/28/13	12:00	10	0.00	11.60	0.00	0.000	4.64	0%
11/29/13	18:00	11	0.00	11.60	0.00	0.000	4.64	0%
11/30/13	12:00	12	0.00	11.60	0.00	0.000	4.64	0%
12/1/13	16:00	13	0.00	11.60	0.00	0.000	4.64	0%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
12/2/13	12:00	14	0.00	11.60	0.00	0.000	4.64	0%
12/3/13	8:00	15	0.00	11.60	0.00	0.000	4.64	0%
12/3/13	21:00	15	0.00	11.60	0.00	0.000	4.64	0%
12/4/13	8:00	16	0.00	11.60	0.00	0.000	4.64	0%
12/4/13	21:00	16	0.00	11.60	0.00	0.000	4.64	0%
12/5/13	8:00	17	0.00	11.60	0.00	0.000	4.64	0%
12/6/13	8:00	18	0.00	11.60	0.00	0.000	4.64	0%
12/7/13	19:00	19	0.00	11.60	0.00	0.000	4.64	0%
12/8/13	12:00	20	0.00	11.60	0.00	0.000	4.64	0%
12/8/13	18:00	20	0.09	11.60	0.01	0.000	4.64	0%
12/9/13	8:00	21	0.19	11.60	0.02	0.001	4.64	0%
12/9/13	21:00	21	0.41	11.60	0.04	0.002	4.63	0%
12/10/13	19:00	22	0.24	11.60	0.02	0.001	4.63	0%
12/11/13	19:00	23	0.22	11.60	0.02	0.001	4.63	0%
12/11/13	23:00	23	0.37	11.60	0.03	0.002	4.63	0%
12/12/13	13:00	24	0.19	11.60	0.02	0.001	4.63	0%
12/13/13	18:00	25	0.26	11.60	0.02	0.001	4.63	0%
12/14/13	18:00	26	0.35	11.60	0.03	0.002	4.63	0%
12/15/13	19:00	27	0.11	11.60	0.01	0.000	4.63	0%
12/16/13	19:00	28	0.61	11.60	0.05	0.003	4.63	0%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
12/17/13	8:00	29	0.41	11.60	0.04	0.002	4.63	0%
12/17/13	20:00	29	0.11	11.60	0.01	0.000	4.62	0%
12/18/13	8:00	30	0.61	11.60	0.05	0.003	4.62	0%
12/19/13	8:00	31	0.36	11.60	0.03	0.002	4.62	0%
12/20/13	8:00	32	0.11	11.60	0.01	0.000	4.62	0%
12/21/13	9:00	33	1.12	11.60	0.10	0.005	4.62	0%
12/22/13	19:00	34	0.65	11.60	0.06	0.003	4.61	1%
12/23/13	8:00	35	0.82	11.60	0.07	0.004	4.61	1%
12/24/13	12:00	36	0.41	11.60	0.04	0.002	4.61	1%
12/25/13	8:00	37	1.12	11.60	0.10	0.005	4.60	1%
12/26/13	19:00	38	1.43	11.60	0.12	0.006	4.60	1%
12/27/13	8:00	39	1.12	11.60	0.10	0.005	4.59	1%
12/28/13	8:00	40	2.24	11.60	0.19	0.010	4.58	1%
12/29/13	14:00	41	2.95	11.60	0.25	0.013	4.57	2%
12/30/13	9:00	42	3.05	11.60	0.26	0.013	4.56	2%
12/31/13	9:00	43	3.46	11.60	0.30	0.015	4.54	2%
1/1/14	11:00	44	4.07	11.60	0.35	0.018	4.52	2%
1/2/14	20:00	45	5.69	11.60	0.49	0.025	4.49	3%
1/3/14	19:00	46	5.83	11.60	0.50	0.026	4.46	4%
1/4/14	18:00	47	4.97	11.60	0.43	0.022	4.44	4%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
1/5/14	8:00	48	4.67	11.60	0.40	0.020	4.43	4%
1/5/14	20:00	48	5.16	11.60	0.44	0.023	4.42	5%
1/6/14	8:00	49	5.49	11.60	0.47	0.024	4.41	5%
1/6/14	20:00	49	5.18	11.60	0.45	0.023	4.40	5%
1/7/14	20:00	50	4.98	11.60	0.43	0.022	4.37	6%
1/8/14	8:00	51	5.66	11.60	0.49	0.025	4.36	6%
1/9/14	8:00	52	5.49	11.60	0.47	0.024	4.34	6%
1/10/14	20:00	53	5.34	11.60	0.46	0.023	4.30	7%
1/11/14	8:00	54	5.87	11.60	0.51	0.026	4.29	7%
1/12/14	20:00	55	5.89	11.60	0.51	0.026	4.25	8%
1/13/14	20:00	56	6.22	11.60	0.54	0.027	4.22	9%
1/14/14	20:00	57	6.40	11.60	0.55	0.028	4.19	10%
1/15/14	8:00	58	6.91	11.60	0.60	0.030	4.18	10%
1/16/14	8:00	59	6.39	11.60	0.55	0.028	4.15	10%
1/17/14	8:00	60	6.20	11.60	0.53	0.027	4.12	11%
1/18/14	8:00	61	6.36	11.60	0.55	0.028	4.10	12%
1/19/14	7:00	62	6.30	11.60	0.54	0.028	4.07	12%
1/20/14	8:00	63	7.01	11.60	0.60	0.031	4.04	13%
1/21/14	20:00	64	6.81	11.60	0.59	0.030	3.99	14%
1/22/14	18:00	65	7.34	11.60	0.63	0.032	3.96	15%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
1/23/14	21:00	66	7.21	11.60	0.62	0.032	3.93	15%
1/24/14	8:00	67	6.60	11.60	0.57	0.029	3.91	16%
1/25/14	14:00	68	7.21	11.60	0.62	0.032	3.88	16%
1/26/14	8:00	69	7.31	11.60	0.63	0.032	3.85	17%
1/27/14	8:00	70	7.62	11.60	0.66	0.033	3.82	18%
1/28/14	8:00	71	6.73	11.60	0.58	0.030	3.79	18%
1/29/14	8:00	72	7.01	11.60	0.60	0.031	3.76	19%
1/30/14	8:00	73	6.50	11.60	0.56	0.028	3.73	20%
1/31/14	8:00	74	6.91	11.60	0.60	0.030	3.70	20%
2/1/14	21:00	75	6.52	11.60	0.56	0.029	3.65	21%
2/2/14	20:00	76	6.81	11.60	0.59	0.030	3.63	22%
2/3/14	20:00	77	6.30	11.60	0.54	0.028	3.60	22%
2/4/14	19:00	78	7.56	11.60	0.65	0.033	3.57	23%
2/5/14	9:00	79	7.52	11.60	0.65	0.033	3.55	23%
2/6/14	8:00	80	7.92	11.60	0.68	0.035	3.51	24%
2/7/14	8:00	81	7.62	11.60	0.66	0.033	3.48	25%
2/8/14	21:00	82	7.72	11.60	0.67	0.034	3.43	26%
2/9/14	8:00	83	7.21	11.60	0.62	0.032	3.41	26%
2/10/14	8:00	84	7.52	11.60	0.65	0.033	3.38	27%
2/11/14	7:30	85	7.21	11.60	0.62	0.032	3.35	28%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
2/12/14	21:00	86	7.37	11.60	0.64	0.032	3.30	29%
2/13/14	8:00	87	7.28	11.60	0.63	0.032	3.29	29%
2/14/14	8:00	88	7.42	11.60	0.64	0.033	3.25	30%
2/15/14	21:00	89	7.11	11.60	0.61	0.031	3.20	31%
2/16/14	21:30	90	7.23	11.60	0.62	0.032	3.17	32%
2/17/14	18:30	91	6.71	11.60	0.58	0.029	3.15	32%
2/18/14	6:00	92	6.60	11.60	0.57	0.029	3.13	32%
2/19/14	8:00	93	7.31	11.60	0.63	0.032	3.10	33%
2/20/14	8:00	94	6.62	11.60	0.57	0.029	3.07	34%
2/21/14	8:00	95	6.30	11.60	0.54	0.028	3.04	34%
2/22/14	8:00	96	6.91	11.60	0.60	0.030	3.01	35%
2/23/14	8:00	97	5.89	11.60	0.51	0.026	2.99	36%
2/24/14	8:00	98	4.37	11.60	0.38	0.019	2.97	36%
2/25/14	8:00	99	5.44	11.60	0.47	0.024	2.94	37%
2/26/14	8:00	100	5.18	11.60	0.45	0.023	2.92	37%
2/27/14	8:00	101	5.39	11.60	0.46	0.024	2.90	38%
2/28/14	8:00	102	4.88	11.60	0.42	0.021	2.87	38%
3/1/14	8:00	103	5.12	11.60	0.44	0.022	2.85	38%
3/2/14	21:00	104	5.28	11.60	0.46	0.023	2.82	39%
3/3/14	18:00	105	5.39	11.60	0.46	0.024	2.80	40%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
3/4/14	20:00	106	4.98	11.60	0.43	0.022	2.77	40%
3/5/14	19:00	107	4.82	11.60	0.42	0.021	2.75	41%
3/6/14	18:00	108	4.27	11.60	0.37	0.019	2.73	41%
3/7/14	21:00	109	4.47	11.60	0.39	0.020	2.71	42%
3/8/14	8:00	110	4.27	11.60	0.37	0.019	2.70	42%
3/9/14	14:00	111	3.96	11.60	0.34	0.017	2.68	42%
3/10/14	8:00	112	3.81	11.60	0.33	0.017	2.67	42%
3/11/14	8:00	113	3.46	11.60	0.30	0.015	2.65	43%
3/12/14	8:00	114	3.66	11.60	0.32	0.016	2.64	43%
3/13/14	8:00	115	3.63	11.60	0.31	0.016	2.62	43%
3/14/14	10:00	116	3.76	11.60	0.32	0.016	2.60	44%
3/15/14	20:00	117	3.86	11.60	0.33	0.017	2.58	44%
3/16/14	16:00	118	3.46	11.60	0.30	0.015	2.57	45%
3/17/14	18:00	119	3.96	11.60	0.34	0.017	2.55	45%
3/18/14	21:00	120	3.96	11.60	0.34	0.017	2.53	45%
3/19/14	8:00	121	3.32	11.60	0.29	0.015	2.52	46%
3/20/14	14:00	122	3.56	11.60	0.31	0.016	2.50	46%
3/21/14	21:00	123	3.25	11.60	0.28	0.014	2.48	46%
3/22/14	8:00	124	3.36	11.60	0.29	0.015	2.48	47%
3/23/14	8:00	125	3.25	11.60	0.28	0.014	2.46	47%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
3/24/14	21:00	126	3.12	11.60	0.27	0.014	2.44	47%
3/25/14	21:30	127	3.17	11.60	0.27	0.014	2.43	48%
3/26/14	18:30	128	3.15	11.60	0.27	0.014	2.42	48%
3/27/14	6:00	129	3.15	11.60	0.27	0.014	2.41	48%
3/28/14	8:00	130	3.03	11.60	0.26	0.013	2.40	48%
3/29/14	8:00	131	3.15	11.60	0.27	0.014	2.38	49%
3/30/14	8:00	132	3.25	11.60	0.28	0.014	2.37	49%
3/31/14	8:00	133	3.01	11.60	0.26	0.013	2.35	49%
4/1/14	8:00	134	2.89	11.60	0.25	0.013	2.34	50%
4/2/14	8:00	135	2.64	11.60	0.23	0.012	2.33	50%
4/3/14	8:00	136	2.95	11.60	0.25	0.013	2.32	50%
4/4/14	8:00	137	3.05	11.60	0.26	0.013	2.30	50%
4/5/14	8:00	138	2.89	11.60	0.25	0.013	2.29	51%
4/6/14	8:00	139	2.75	11.60	0.24	0.012	2.28	51%
4/7/14	8:00	140	2.77	11.60	0.24	0.012	2.27	51%
4/8/14	21:00	141	2.60	11.60	0.22	0.011	2.25	51%
4/9/14	18:00	142	2.57	11.60	0.22	0.011	2.24	52%
4/10/14	20:00	143	2.57	11.60	0.22	0.011	2.23	52%
4/11/14	19:00	144	2.55	11.60	0.22	0.011	2.22	52%
4/12/14	18:00	145	2.52	11.60	0.22	0.011	2.21	52%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
4/13/14	8:00	146	2.61	11.60	0.23	0.011	2.20	53%
4/14/14	19:00	147	2.14	11.60	0.18	0.009	2.19	53%
4/15/14	8:00	148	2.14	11.60	0.18	0.009	2.18	53%
4/16/14	8:00	149	2.03	11.60	0.18	0.009	2.17	53%
4/17/14	7:00	150	2.09	11.60	0.18	0.009	2.16	53%
4/18/14	9:00	151	2.04	11.60	0.18	0.009	2.15	54%
4/19/14	9:00	152	2.00	11.60	0.17	0.009	2.14	54%
4/20/14	8:00	153	2.00	11.60	0.17	0.009	2.14	54%
4/21/14	8:00	154	1.97	11.60	0.17	0.009	2.13	54%
4/22/14	8:00	155	1.83	11.60	0.16	0.008	2.12	54%
4/23/14	8:00	156	1.69	11.60	0.15	0.007	2.11	54%
4/24/14	8:00	157	1.73	11.60	0.15	0.008	2.10	55%
4/25/14	8:00	158	1.83	11.60	0.16	0.008	2.10	55%
4/26/14	8:00	159	1.73	11.60	0.15	0.008	2.09	55%
4/27/14	8:00	160	1.83	11.60	0.16	0.008	2.08	55%
4/28/14	8:00	161	1.78	11.60	0.15	0.008	2.07	55%
4/29/14	8:00	162	1.63	11.60	0.14	0.007	2.07	55%
4/30/14	8:00	163	1.53	11.60	0.13	0.007	2.06	56%
5/1/14	8:00	164	1.43	11.60	0.12	0.006	2.05	56%
5/2/14	8:00	165	1.53	11.60	0.13	0.007	2.05	56%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
5/3/14	8:00	166	1.52	11.60	0.13	0.007	2.04	56%
5/4/14	8:00	167	1.32	11.60	0.11	0.006	2.03	56%
5/5/14	8:00	168	1.43	11.60	0.12	0.006	2.03	56%
5/6/14	8:00	169	1.24	11.60	0.11	0.005	2.02	56%
5/7/14	8:00	170	1.32	11.60	0.11	0.006	2.02	57%
5/8/14	8:00	171	1.43	11.60	0.12	0.006	2.01	57%
5/9/14	8:00	172	1.36	11.60	0.12	0.006	2.00	57%
5/10/14	8:00	173	1.43	11.60	0.12	0.006	2.00	57%
5/11/14	21:00	174	1.43	11.60	0.12	0.006	1.99	57%
5/12/14	18:00	175	1.63	11.60	0.14	0.007	1.98	57%
5/13/14	20:00	176	1.43	11.60	0.12	0.006	1.97	57%
5/14/14	19:00	177	1.54	11.60	0.13	0.007	1.97	58%
5/15/14	18:00	178	1.43	11.60	0.12	0.006	1.96	58%
5/16/14	21:00	179	1.32	11.60	0.11	0.006	1.96	58%
5/17/14	8:00	180	1.43	11.60	0.12	0.006	1.95	58%
5/18/14	14:00	181	1.22	11.60	0.11	0.005	1.95	58%
5/19/14	8:00	182	1.43	11.60	0.12	0.006	1.94	58%
5/20/14	8:00	183	1.32	11.60	0.11	0.006	1.94	58%
5/21/14	8:00	184	1.17	11.60	0.10	0.005	1.93	58%
5/22/14	8:00	185	1.21	11.60	0.10	0.005	1.93	58%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
5/23/14	10:00	186	1.12	11.60	0.10	0.005	1.92	59%
5/24/14	20:00	187	1.02	11.60	0.09	0.004	1.91	59%
5/25/14	16:00	188	1.12	11.60	0.10	0.005	1.91	59%
5/26/14	18:00	189	1.28	11.60	0.11	0.006	1.90	59%
5/27/14	21:00	190	1.32	11.60	0.11	0.006	1.90	59%
5/28/14	8:00	191	1.43	11.60	0.12	0.006	1.89	59%
5/29/14	14:00	192	1.12	11.60	0.10	0.005	1.89	59%
5/30/14	21:00	193	0.82	11.60	0.07	0.004	1.88	59%
5/31/14	8:00	194	0.91	11.60	0.08	0.004	1.88	59%
6/1/14	8:00	195	1.02	11.60	0.09	0.004	1.88	60%
6/2/14	7:30	196	1.12	11.60	0.10	0.005	1.87	60%
6/3/14	21:00	197	1.23	11.60	0.11	0.005	1.86	60%
6/4/14	8:00	198	1.12	11.60	0.10	0.005	1.86	60%
6/5/14	8:00	199	0.92	11.60	0.08	0.004	1.86	60%
6/6/14	21:00	200	1.02	11.60	0.09	0.004	1.85	60%
6/7/14	21:30	201	1.12	11.60	0.10	0.005	1.85	60%
6/8/14	18:30	202	1.32	11.60	0.11	0.006	1.84	60%
6/9/14	6:00	203	1.26	11.60	0.11	0.006	1.84	60%
6/10/14	8:00	204	1.12	11.60	0.10	0.005	1.83	60%
6/11/14	8:00	205	1.12	11.60	0.10	0.005	1.83	61%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
6/12/14	8:00	206	1.07	11.60	0.09	0.005	1.82	61%
6/13/14	8:00	207	1.02	11.60	0.09	0.004	1.82	61%
6/14/14	8:00	208	1.12	11.60	0.10	0.005	1.81	61%
6/15/14	8:00	209	1.22	11.60	0.11	0.005	1.81	61%
6/16/14	8:00	210	0.98	11.60	0.08	0.004	1.80	61%
6/17/14	8:00	211	0.82	11.60	0.07	0.004	1.80	61%
6/18/14	7:30	212	0.61	11.60	0.05	0.003	1.80	61%
6/19/14	21:00	213	0.72	11.60	0.06	0.003	1.79	61%
6/20/14	14:00	214	0.82	11.60	0.07	0.004	1.79	61%
6/21/14	14:00	215	0.51	11.60	0.04	0.002	1.79	61%
6/22/14	8:00	216	0.61	11.60	0.05	0.003	1.79	61%
6/23/14	8:00	217	0.51	11.60	0.04	0.002	1.78	62%
6/24/14	8:00	218	0.41	11.60	0.04	0.002	1.78	62%
6/25/14	8:00	219	0.36	11.60	0.03	0.002	1.78	62%
6/26/14	10:00	220	0.24	11.60	0.02	0.001	1.78	62%
6/27/14	20:00	221	0.13	11.60	0.01	0.001	1.78	62%
6/28/14	8:00	222	0.13	11.60	0.01	0.001	1.78	62%
6/29/14	8:00	223	0.1	11.60	0.01	0.000	1.78	62%
6/30/14	8:00	224	0.08	11.60	0.01	0.000	1.78	62%
7/1/14	8:00	225	0.06	11.60	0.01	0.000	1.78	62%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
7/2/14	10:00	226	0.03	11.60	0.00	0.000	1.78	62%
7/3/14	20:00	227	0	11.60	0.00	0.000	1.78	62%
7/4/14	16:00	228	0.01	11.60	0.00	0.000	1.78	62%
7/5/14	18:00	229	0	11.60	0.00	0.000	1.78	62%
7/6/14	21:00	230	0.01	11.60	0.00	0.000	1.78	62%
7/7/14	8:00	231	0	11.60	0.00	0.000	1.78	62%
7/8/14	14:00	232	0	11.60	0.00	0.000	1.78	62%
7/9/14	21:00	233	0	11.60	0.00	0.000	1.78	62%
7/10/14	8:00	234	0.01	11.60	0.00	0.000	1.78	62%
7/11/14	8:00	235	0	11.60	0.00	0.000	1.78	62%
7/12/14	21:00	236	0	11.60	0.00	0.000	1.78	62%
7/13/14	21:30	237	0	11.60	0.00	0.000	1.78	62%
7/14/14	18:30	238	0.01	11.60	0.00	0.000	1.78	62%
7/15/14	6:00	239	0	11.60	0.00	0.000	1.78	62%
7/16/14	8:00	240	0	11.60	0.00	0.000	1.78	62%
7/17/14	8:00	241	0	11.60	0.00	0.000	1.78	62%
7/18/14	8:00	242	0	11.60	0.00	0.000	1.78	62%
7/19/14	8:00	243	0.01	11.60	0.00	0.000	1.78	62%
7/20/14	8:00	244	0	11.60	0.00	0.000	1.78	62%
7/21/14	21:00	245	0	11.60	0.00	0.000	1.78	62%

Table B.2.3 Record of Gas Flow Readings – Moderately Deg. Bioreactors (continued)

Gas Flow Meter Readings – Moderately Deg. Flow Meter								
Date	**Time**	**Cum. Days**	**CH_4 Flow Reading [sccm]**	**Dry Wt in Reactors [lb]**	**CH_4 Flow Rate/Waste [sccm/lb]**	**CH_4 Flow Rate/Waste [ft^3/lb] per day**	**CH_4 remaining [ft^3/lb]**	**% of Theoretical Total**
7/22/14	18:00	246	0	11.60	0.00	0.000	1.78	62%
7/23/14	20:00	247	0	11.60	0.00	0.000	1.78	62%
7/24/14	19:00	248	0	11.60	0.00	0.000	1.78	62%
7/25/14	18:00	249	0	11.60	0.00	0.000	1.78	62%
7/26/14	21:00	250	0.01	11.60	0.00	0.000	1.78	62%
7/27/14	8:00	251	0	11.60	0.00	0.000	1.78	62%
7/28/14	14:00	252	0	11.60	0.00	0.000	1.78	62%
7/29/14	8:00	253	0	11.60	0.00	0.000	1.78	62%
7/30/14	8:00	254	0	11.60	0.00	0.000	1.78	62%
7/31/14	8:00	255	0	11.60	0.00	0.000	1.78	62%
8/1/14	8:00	256	0.01	11.60	0.00	0.000	1.78	62%
8/2/14	10:00	257	0	11.60	0.00	0.000	1.78	62%
8/3/14	20:00	258	0	11.60	0.00	0.000	1.78	62%
8/4/14	16:00	259	0	11.60	0.00	0.000	1.78	62%
8/5/14	18:00	260	0	11.60	0.00	0.000	1.78	62%
8/6/14	21:00	261	0	11.60	0.00	0.000	1.78	62%

B.3 Gas Bag Records

Tables B.3.1 through B.3.3 tabulate records for secondary gas bags used in series after gas flow meters for composite, readily, and moderately degradable bioreactor sets. Table B.3.4 tabulates records for gas bags used as the primary means of establishing volume of total gas produced by the slowly degradable bioreactor set. Gas bags utilized for the experiment consisted of tedlar bags with single polypropylene fittings, as manufactured by SKC Incorporated. Various capacity bags were used, including 1 liter, 10 liter, and 50 liter bags, depending on the volume of flow anticipated. Lower capacity bags were used at the beginning and end of the experiment to capture the gas as it was emitted at lower flow rates.

Based on manufacturer recommendations, proper inflation of the gas bag would result in 80 percent of the rated total capacity. Therefore, proper inflation would result in gas bag volumes of 0.8, 8, and 40 liters, respectively. In select circumstances, the rate of gas production did not allow a full bag to be swapped out for an empty bag causing this recommendation to be exceeded and be filled to total rated capacity. These occurrences were noted, and the total rated capacity of the bag was used. Figure B.3.1 illustrates the manufacturer's recommendation for inflation.

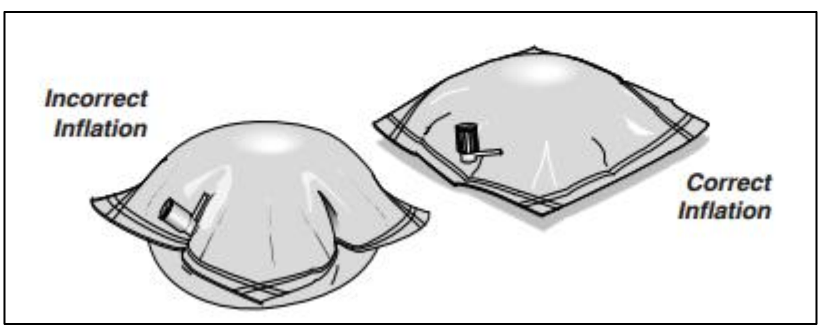

Figure B.3.1 Manufacturer's (SKC) Recommendation For Inflation of Gas Bags

Table B.3.1 Record of Total Gas Flow Volume Captured – Composite Bioreactors

Date	Dry Weight Waste	Cumulative No. of Days	Bag Volume	Actual Bag Vol	Cumulative Volume of Gas [L]	Cumulative Volume of Gas [ft^3]	Cumulative Volume of Gas per LB Waste [ft^3/lb]	Average Daily Volume (ft^3/day)	Average Daily Flow Rate [ft^3/lb]
11/27/13	27.32	9	1	0.8	0.8	0.038	0.001	0.004	0.000
12/2/13	27.32	14	50	40	40.8	1.914	0.070	0.375	0.014
12/5/13	27.32	17	50	40	80.8	3.790	0.139	0.625	0.023
12/7/13	27.32	19	50	40	120.8	5.667	0.207	0.938	0.034
12/8/13	27.32	20	50	40	160.8	7.543	0.276	1.876	0.069
12/9/13	27.32	21	50	45	205.8	9.654	0.353	2.111	0.077
12/10/13	27.32	22	50	40	245.8	11.531	0.422	1.876	0.069
12/11/13	27.32	23	50	30	275.8	12.938	0.474	1.407	0.052
12/12/13	27.32	24	50	30	305.8	14.345	0.525	1.407	0.052
12/13/13	27.32	25	50	40	345.8	16.222	0.594	1.876	0.069
12/14/13	27.32	26	50	40	385.8	18.098	0.662	1.876	0.069
12/15/13	27.32	27	50	40	425.8	19.975	0.731	1.876	0.069
12/16/13	27.32	28	50	45	470.8	22.086	0.808	2.111	0.077
12/17/13	27.32	29	50	40	510.8	23.962	0.877	1.876	0.069
12/17/13	27.32	29.5	50	40	550.8	25.839	0.946	3.753	0.137
12/18/13	27.32	30	50	40	590.8	27.715	1.014	3.753	0.137
12/18/13	27.32	30.5	50	40	630.8	29.592	1.083	3.753	0.137
12/19/13	27.32	31	50	40	670.8	31.468	1.152	3.753	0.137
12/19/13	27.32	31.5	50	40	710.8	33.345	1.221	3.753	0.137
12/20/13	27.32	32	50	40	750.8	35.221	1.289	3.753	0.137

Table B.3.1 Record of Total Gas Flow Volume Captured – Composite Bioreactors (continued)

Date	Dry Weight Waste	Cumulative No. of Days	Bag Volume	Actual Bag Vol	Cumulative Volume of Gas [L]	Cumulative Volume of Gas [ft^3]	Cumulative Volume of Gas per LB Waste [ft^3/lb]	Average Daily Volume (ft^3/day)	Average Daily Flow Rate [ft^3/lb]
12/21/13	27.32	33	50	40	790.8	37.098	1.358	1.876	0.069
12/22/13	27.32	34	50	40	830.8	38.974	1.427	1.876	0.069
12/24/13	27.32	36	50	40	870.8	40.850	1.495	0.938	0.034
12/25/13	27.32	37	50	40	910.8	42.727	1.564	1.876	0.069
12/26/13	27.32	38	50	40	950.8	44.603	1.633	1.876	0.069
12/27/13	27.32	39	50	40	990.8	46.480	1.701	1.876	0.069
12/28/13	27.32	40	50	45	1035.8	48.591	1.779	2.111	0.077
12/30/13	27.32	42	50	40	1075.8	50.467	1.847	0.938	0.034
12/31/13	27.32	43	50	40	1115.8	52.344	1.916	1.876	0.069
1/1/14	27.32	44	50	40	1155.8	54.220	1.985	1.876	0.069
1/2/14	27.32	45	50	40	1195.8	56.097	2.053	1.876	0.069
1/3/14	27.32	46	50	40	1235.8	57.973	2.122	1.876	0.069
1/4/14	27.32	47	50	40	1275.8	59.850	2.191	1.876	0.069
1/5/14	27.32	48	50	45	1320.8	61.961	2.268	2.111	0.077
1/6/14	27.32	49	50	45	1365.8	64.072	2.345	2.111	0.077
1/7/14	25.61	50	50	45	1410.8	66.183	2.428	2.111	0.082
1/9/14	25.61	52	50	45	1455.8	68.294	2.510	1.056	0.041
1/10/14	25.61	53	50	40	1495.8	70.170	2.583	1.876	0.073
1/12/14	25.61	55	50	40	1535.8	72.046	2.657	0.938	0.037
1/14/14	25.61	57	50	40	1575.8	73.923	2.730	0.938	0.037

Table B.3.1 Record of Total Gas Flow Volume Captured – Composite Bioreactors (continued)

Date	Dry Weight Waste	Cumulative No. of Days	Bag Volume	Actual Bag Vol	Cumulative Volume of Gas [L]	Cumulative Volume of Gas [ft^3]	Cumulative Volume of Gas per LB Waste [ft^3/lb]	Average Daily Volume (ft^3/day)	Average Daily Flow Rate [ft^3/lb]
1/16/14	25.61	59	50	40	1615.8	75.799	2.803	0.938	0.037
1/18/14	25.61	61	50	40	1655.8	77.676	2.876	0.938	0.037
1/19/14	23.89	62	50	40	1695.8	79.552	2.955	1.876	0.079
1/21/14	23.89	64	50	40	1735.8	81.429	3.034	0.938	0.039
1/22/14	23.89	65	50	40	1775.8	83.305	3.112	1.876	0.079
1/24/14	23.89	67	50	40	1815.8	85.182	3.191	0.938	0.039
1/26/14	23.89	69	50	40	1855.8	87.058	3.269	0.938	0.039
1/28/14	23.89	71	50	40	1895.8	88.935	3.348	0.938	0.039
1/30/14	23.89	73	50	40	1935.8	90.811	3.426	0.938	0.039
2/2/14	23.89	76	50	40	1975.8	92.687	3.505	0.625	0.026
2/5/14	23.89	79	50	45	2020.8	94.798	3.593	0.704	0.029
2/8/14	23.89	82	50	40	2060.8	96.675	3.672	0.625	0.026
2/11/14	23.89	85	50	40	2100.8	98.551	3.750	0.625	0.026
2/13/14	23.89	87	50	40	2140.8	100.428	3.829	0.938	0.039
2/17/14	23.89	91	50	40	2180.8	102.304	3.907	0.469	0.020
2/21/14	21.38	95	50	40	2220.8	104.181	3.995	0.469	0.022
2/24/14	21.38	98	50	40	2260.8	106.057	4.083	0.625	0.029
2/27/14	21.38	101	50	40	2300.8	107.934	4.171	0.625	0.029
3/3/14	21.38	105	50	40	2340.8	109.810	4.258	0.469	0.022
3/7/14	21.38	109	50	40	2380.8	111.687	4.346	0.469	0.022

Table B.3.1 Record of Total Gas Flow Volume Captured – Composite Bioreactors (continued)

Date	**Dry Weight Waste**	**Cumulative No. of Days**	**Bag Volume**	**Actual Bag Vol**	**Cumulative Volume of Gas [L]**	**Cumulative Volume of Gas [ft^3]**	**Cumulative Volume of Gas per LB Waste [ft^3/lb]**	**Average Daily Volume (ft^3/day)**	**Average Daily Flow Rate [ft^3/lb]**
3/12/14	21.38	114	50	40	2420.8	113.563	4.434	0.375	0.018
3/17/14	21.38	119	50	45	2465.8	115.674	4.533	0.422	0.020
3/21/14	19.66	123	50	45	2510.8	117.785	4.640	0.528	0.027
3/27/14	19.66	129	50	40	2550.8	119.661	4.736	0.313	0.016
4/3/14	19.66	136	50	45	2595.8	121.772	4.843	0.302	0.015
4/10/14	19.66	143	50	45	2640.8	123.884	4.950	0.302	0.015
4/19/14	19.66	152	50	40	2680.8	125.760	5.046	0.208	0.011
5/1/14	19.66	164	50	40	2720.8	127.636	5.141	0.156	0.008
5/18/14	19.66	181	50	40	2760.8	129.513	5.237	0.110	0.006
6/27/14	17.94	221	50	40	2800.8	131.389	5.332	0.047	0.003

Table B.3.2 Record of Total Gas Flow Volume Captured – Readily Deg. Bioreactors

Date	Dry Weight Waste	Cumulative No. of Days	Bag Volume	Actual Bag Vol	Cumulative Volume of Gas [L]	Cumulative Volume of Gas [ft^3]	Cumulative Volume of Gas per LB Waste [ft^3/lb]	Average Daily Volume (ft^3/day)	Average Daily Flow Rate [ft^3/lb]
11/20/13	11.48	2	1	0.8	0.8	0.038	0.00	0.019	0.002
11/22/13	11.48	4	1	0.8	1.6	0.075	0.01	0.019	0.002
11/23/13	11.48	5	1	0.8	2.4	0.113	0.01	0.038	0.003
11/30/13	11.48	12	50	40	42.4	1.989	0.17	0.268	0.023
12/4/13	11.48	16	50	40	82.4	3.865	0.34	0.469	0.041
12/5/13	11.48	17	50	40	122.4	5.742	0.50	1.876	0.163
12/7/13	11.48	19	50	50	172.4	8.088	0.70	1.173	0.102
12/8/13	11.48	20	50	40	212.4	9.964	0.87	1.876	0.163
12/9/13	11.48	21	50	40	252.4	11.840	1.03	1.876	0.163
12/10/13	11.48	22	50	40	292.4	13.717	1.19	1.876	0.163
12/11/13	11.48	23	50	50	342.4	16.062	1.40	2.346	0.204
12/12/13	11.48	24	50	40	382.4	17.939	1.56	1.876	0.163
12/13/13	11.48	25	50	50	432.4	20.284	1.77	2.346	0.204
12/14/13	11.48	26	50	50	482.4	22.630	1.97	2.346	0.204
12/15/13	11.48	27	50	50	532.4	24.976	2.18	2.346	0.204
12/16/13	11.48	28	50	50	582.4	27.321	2.38	2.346	0.204
12/17/13	11.48	29	50	40	622.4	29.198	2.54	1.876	0.163
12/18/13	11.48	30	50	50	672.4	31.543	2.75	2.346	0.204
12/19/13	11.48	31	50	50	722.4	33.889	2.95	2.346	0.204
12/20/13	11.48	32	50	50	772.4	36.234	3.16	2.346	0.204

Table B.3.2 Record of Total Gas Flow Volume Captured – Readily Deg. Bioreactors (continued)

Date	Dry Weight Waste	Cumulative No. of Days	Bag Volume	Actual Bag Vol	Cumulative Volume of Gas [L]	Cumulative Volume of Gas [ft^3]	Cumulative Volume of Gas per LB Waste [ft^3/lb]	Average Daily Volume (ft^3/day)	Average Daily Flow Rate [ft^3/lb]
12/21/13	11.48	33	50	50	822.4	38.580	3.36	2.346	0.204
12/22/13	11.48	34	50	50	872.4	40.925	3.56	2.346	0.204
12/23/13	11.48	35	50	50	922.4	43.271	3.77	2.346	0.204
12/24/13	11.48	36	50	50	972.4	45.617	3.97	2.346	0.204
12/25/13	11.48	37	50	50	1022.4	47.962	4.18	2.346	0.204
12/26/13	11.48	38	50	50	1072.4	50.308	4.38	2.346	0.204
12/27/13	11.48	39	50	50	1122.4	52.653	4.59	2.346	0.204
12/28/13	11.48	40	50	50	1172.4	54.999	4.79	2.346	0.204
12/29/13	11.48	41	50	40	1212.4	56.875	4.95	1.876	0.163
12/30/13	11.48	42	50	40	1252.4	58.752	5.12	1.876	0.163
12/31/13	11.48	43	50	40	1292.4	60.628	5.28	1.876	0.163
1/1/14	11.48	44	50	40	1332.4	62.505	5.44	1.876	0.163
1/2/14	11.48	45	50	50	1382.4	64.850	5.65	2.346	0.204
1/3/14	11.48	46	50	40	1422.4	66.727	5.81	1.876	0.163
1/4/14	11.48	47	50	40	1462.4	68.603	5.98	1.876	0.163
1/5/14	11.48	48	50	40	1502.4	70.480	6.14	1.876	0.163
1/6/14	11.48	49	50	30	1532.4	71.887	6.26	1.407	0.123
1/8/14	11.48	51	50	40	1572.4	73.763	6.43	0.938	0.082
1/10/14	11.48	53	50	40	1612.4	75.640	6.59	0.938	0.082
1/12/14	11.48	55	50	40	1652.4	77.516	6.75	0.938	0.082

Table B.3.2 Record of Total Gas Flow Volume Captured – Readily Deg. Bioreactors (continued)

Date	Dry Weight Waste	Cumulative No. of Days	Bag Volume	Actual Bag Vol	Cumulative Volume of Gas [L]	Cumulative Volume of Gas [ft^3]	Cumulative Volume of Gas per LB Waste [ft^3/lb]	Average Daily Volume (ft^3/day)	Average Daily Flow Rate [ft^3/lb]
1/14/14	11.48	57	50	30	1682.4	78.924	6.87	0.704	0.061
1/16/14	11.48	59	50	30	1712.4	80.331	7.00	0.704	0.061
1/19/14	11.48	62	50	50	1762.4	82.677	7.20	0.782	0.068
1/22/14	11.48	65	50	40	1802.4	84.553	7.37	0.625	0.054
1/26/14	11.48	69	50	40	1842.4	86.429	7.53	0.469	0.041
1/30/14	11.48	73	50	40	1882.4	88.306	7.69	0.469	0.041
2/4/14	11.48	78	50	40	1922.4	90.182	7.86	0.375	0.033
2/11/14	11.48	85	50	40	1962.4	92.059	8.02	0.268	0.023
2/16/14	11.48	90	50	40	2002.4	93.935	8.18	0.375	0.033
2/25/14	11.48	99	50	40	2042.4	95.812	8.35	0.208	0.018
3/7/14	11.48	109	50	40	2082.4	97.688	8.51	0.188	0.016
3/23/14	11.48	125	50	40	2122.4	99.565	8.67	0.117	0.010
4/13/14	11.48	146	50	40	2162.4	101.441	8.84	0.089	0.008
6/27/14	11.48	221	50	10	2172.4	101.910	8.88	0.006	0.001

Table B.3.3 Record of Total Gas Flow Volume Captured –Moderately Deg. Bioreactors

Date	Dry Weight Waste	Cumulative No. of Days	Bag Volume	Actual Bag Vol	Cumulative Volume of Gas [L]	Cumulative Volume of Gas [ft^3]	Cumulative Volume of Gas per LB Waste [ft^3/lb]	Average Daily Volume (ft^3/day)	Average Daily Flow Rate [ft^3/lb]
11/27/13	11.6	9	1	0.8	0.8	0.038	0.00	0.004	0.000
12/4/13	11.6	16	1	0.8	1.6	0.075	0.01	0.005	0.000
12/9/13	11.6	21	1	0.8	2.4	0.113	0.01	0.008	0.001
12/10/13	11.6	22	1	0.8	3.2	0.150	0.01	0.038	0.003
12/26/13	11.6	38	50	40	43.2	2.027	0.17	0.117	0.010
1/1/14	11.6	44	50	40	83.2	3.903	0.34	0.313	0.027
1/4/14	11.6	47	50	40	123.2	5.779	0.50	0.625	0.054
1/9/14	11.6	52	50	50	173.2	8.125	0.70	0.469	0.040
1/12/14	11.6	55	50	40	213.2	10.002	0.86	0.625	0.054
1/16/14	11.6	59	50	50	263.2	12.347	1.06	0.586	0.051
1/19/14	11.6	62	50	40	303.2	14.224	1.23	0.625	0.054
1/22/14	11.6	65	50	50	353.2	16.569	1.43	0.782	0.067
1/25/14	11.6	68	50	40	393.2	18.446	1.59	0.625	0.054
1/28/14	11.6	71	50	40	433.2	20.322	1.75	0.625	0.054
1/31/14	11.6	74	50	40	473.2	22.198	1.91	0.625	0.054
2/3/14	11.6	77	50	40	513.2	24.075	2.08	0.625	0.054
2/6/14	11.6	80	50	40	553.2	25.951	2.24	0.625	0.054
2/9/14	11.6	83	50	50	603.2	28.297	2.44	0.782	0.067
2/12/14	11.6	86	50	50	653.2	30.642	2.64	0.782	0.067
2/15/14	11.6	89	50	40	693.2	32.519	2.80	0.625	0.054

Table B.3.3 Record of Total Gas Flow Volume Captured –Moderately Deg. Bioreactors (continued)

Date	Dry Weight Waste	Cumulative No. of Days	Bag Volume	Actual Bag Vol	Cumulative Volume of Gas [L]	Cumulative Volume of Gas [ft^3]	Cumulative Volume of Gas per LB Waste [ft^3/lb]	Average Daily Volume (ft^3/day)	Average Daily Flow Rate [ft^3/lb]
2/18/14	11.6	92	50	40	733.2	34.395	2.97	0.625	0.054
2/21/14	11.6	95	50	50	783.2	36.741	3.17	0.782	0.067
2/24/14	11.6	98	50	40	823.2	38.617	3.33	0.625	0.054
2/28/14	11.6	102	50	40	863.2	40.494	3.49	0.469	0.040
3/3/14	11.6	105	50	40	903.2	42.370	3.65	0.625	0.054
3/8/14	11.6	110	50	40	943.2	44.247	3.81	0.375	0.032
3/14/14	11.6	116	50	50	993.2	46.592	4.02	0.391	0.034
3/19/14	11.6	121	50	40	1033.2	48.469	4.18	0.375	0.032
3/25/14	11.6	127	50	40	1073.2	50.345	4.34	0.313	0.027
4/2/14	11.6	135	50	40	1113.2	52.222	4.50	0.235	0.020
4/9/14	11.6	142	50	40	1153.2	54.098	4.66	0.268	0.023
4/16/14	11.6	149	50	40	1193.2	55.975	4.83	0.268	0.023
4/27/14	11.6	160	50	40	1233.2	57.851	4.99	0.171	0.015
5/8/14	11.6	171	50	40	1273.2	59.728	5.15	0.171	0.015
5/21/14	11.6	184	50	40	1313.2	61.604	5.31	0.144	0.012
6/7/14	11.6	201	50	40	1353.2	63.480	5.47	0.110	0.010
7/4/14	11.6	228	50	40	1393.2	65.357	5.63	0.069	0.006
8/1/14	11.6	256	50	40	1433.2	67.233	5.80	0.067	0.006

Table B.3.4 Record of Total Gas Flow Volume Captured – Slowly Deg. Bioreactors

Date	Dry Weight Waste	Cumulative No. of Days	Bag Volume	Actual Bag Vol	Cumulative Volume of Gas [L]	Cumulative Volume of Gas [ft^3]	Cumulative Volume of Gas per LB Waste [ft^3/lb]	Average Daily Volume (ft^3/day)	Average Daily Flow Rate [ft^3/lb]
12/20/13	7.68	32	1	0.8	0.8	0.038	0.00489	0.00117	0.00015
1/17/14	7.68	60	1	0.8	1.6	0.075	0.00977	0.00134	0.00017
2/9/14	7.68	83	1	0.8	2.4	0.113	0.01466	0.00163	0.00021
2/23/14	7.68	97	1	0.8	3.2	0.150	0.01955	0.00268	0.00035
3/9/14	7.68	111	1	0.8	4	0.188	0.02443	0.00268	0.00035
3/14/14	7.68	116	1	0.8	4.8	0.225	0.02932	0.00751	0.00098
3/28/14	7.68	130	1	0.8	5.6	0.263	0.03421	0.00268	0.00035
4/10/14	7.68	143	1	0.8	6.4	0.300	0.03909	0.00289	0.00038
4/24/14	7.68	157	1	0.8	7.2	0.338	0.04398	0.00268	0.00035
5/8/14	7.68	171	1	0.8	8	0.375	0.04887	0.00268	0.00035
5/23/14	7.68	186	1	0.8	8.8	0.413	0.05375	0.00250	0.00033
6/7/14	7.68	201	1	0.8	9.6	0.450	0.05864	0.00250	0.00033
6/23/14	7.68	217	1	0.8	10.4	0.488	0.06353	0.00235	0.00031
7/8/14	7.68	232	1	0.8	11.2	0.525	0.06841	0.00250	0.00033
7/27/14	7.68	251	1	0.8	12	0.563	0.07330	0.00198	0.00026
8/14/14	7.68	269	1	0.8	12.8	0.600	0.07819	0.00208	0.00027

B.4 Gas Composition Records

Tables B.4.1 and B.4.2 tabulate the results of periodic gas composition testing of the secondary gas collection bags to understand the composition of gas generated and ascertain which phase of decomposition the bioreactor set was undergoing. The phases of decomposition and characteristic gas composition are discussed in Chapter 2. Generally, the gas characterization readings obtained correlated closely with the phase which the bioreactors were assumed to be in during the time of reading.

A landfill gas meter, Landtec model GEM2000+ was used to perform composition analyses. The equipment is typically used by industry and field-proven to monitor landfill gas extraction systems accurately and efficiently. The GEM2000+ samples and analyzes the methane, carbon dioxide, oxygen, carbon monoxide, and hydrogen sulfide content of landfill gas. A unit-mounted LCD screen shows the results as percentages of CH_4, CO_2, O_2 and "balance" gas, and parts per million (ppm) of CO and H_2S. Calibration data for the equipment is provided in Appendix D – Calibration Records for Measuring Devices.

Table B.4.1 Gas Composition Record

Gas Composition Record								
Date of Reading	**Bioreactor**	**Gas Flow Reading [sccm]**	**Approx Tedlar Bag Volume [L]**	**% CH4**	**% CO2**	**CO [ppm]**	**% O2**	**H2S [ppm]**
12/12/13	Composite	10.023	50	37.6	54.2	221	0.01	209
12/12/13	Composite	10.023	50	37.9	54.8	253	0.01	301
12/19/13	Composite	8.113	50	54.6	41.4	12	1	91
12/19/13	Composite	8.113	50	54.2	42	17	0.1	104
12/24/13	Composite	7.106	50	59.7	40.1	0	0.1	80
12/24/13	Composite	7.106	50	58.6	39.7	14	0.04	78
12/22/13	Readily	24.77	50	56.2	49.4	162	0.01	71
12/22/13	Readily	24.77	50	54.7	48.8	152	0.01	68
12/25/13	Composite	4.25	50	54.7	41.2	17	0.7	169
1/25/14	Composite	4.25	50	55.1	41.2	16	0.5	176
2/21/14	Composite	2.785	50	52.3	43.3	27	0.06	184
2/21/14	Composite	2.765	50	54.1	43.2	29	0.06	182
3/25/14	Composite	1.544	50	53.8	42.3	21	0.05	173
3/25/14	Composite	1.544	50	54.1	43	16	0.04	124
4/23/14	Composite	1.85	50	52.3	43.3	17	0.01	29
4/23/14	Composite	1.85	50	52.5	43.1	22	0.02	64
6/16/14	Composite	0.13	50	47.6	38.2	23	.01	13
6/17/14	Composite	0.13	50	47.3	37.9	34	0.01	6
4/27/14	Readily	0.39	1	48.9	37.4	28	0.01	18
4/27/14	Readily	0.39	1	48.8	37.2	36	0.01	9

Table B.4.2 Record of Gas Composition (continued)

Gas Composition Record								
Date of Reading	**Bioreactor**	**Gas Flow Reading [sccm]**	**Approx Tedlar Bag Volume [L]**	**% CH4**	**% CO2**	**CO [ppm]**	**% O2**	**H2S [ppm]**
6/28/14	Readily	0.00	10	45.6	35.7	21	1.3	16
6/28/14	Readily	0.00	10	45.5	35.4	17	1.3	13
3/22/14	Moderately	3.36	50	53.7	42.3	24	0.01	116
3/22/14	Moderately	3.36	50	52.3	44.1	27	0.01	112
6/12/14	Moderately	1.07	50	51.2	40.7	13	0.9	27
6/12/14	Moderately	1.07	50	51	40.3	12	1	17

B.5 Moisture Content Meter Records

Leachate was recirculated continuously throughout the experiment to accelerate the on-set of biodegradation and simulate a bioreactor landfill. Moisture content was maintained between 40 to 45 percent based on recommendations by USEPA (2003) and Reinhart and Townsend (1997), and further discussed in Chapter 3. Moisture content was checked on a weekly basis using a TRIME-PICO64 moisture content probe as manufactured by IMKO GmbH.

Each moisture content probe was installed into one bioreactor representative of each of the four reactor sets. Non-destructive assessment of moisture content using time domain reflectometry equipment for moisture measurement was required as taking a sample of waste to determine moisture content during the experiment would alter the gas production rate of the specific reactor, disrupt microorganism activity, and introduce oxygen into the system which would arrest the biodegradation process. Leachate was recirculated on a weekly basis, or more frequently as indicated by moisture probe readings and required to increase the moisture content of the waste sample to within the recommended limits.

Records maintained during the course of work for each reactor set are provided as Table B.5.1 through B.5.4 for the composite, readily, moderately, and slowly degradable moisture content sets, respectively. Each reading was taken using a handheld electronic reader connected to the embedded moisture content probe. The existing moisture content water was recorded prior to recirculation of leachate and injection of supplementation with new leachate, as needed.

To add leachate, a leachate reservoir was connected to the bioreactor using an attachment consisting of a normally-closed butterfly valve, ¼" tygon tubing, and a second normally-closed butterfly valve. The apparatus was fashioned to create an air-tight seal such that oxygen from atmosphere was not introduced into the bioreactor as it would be fatal to methanogenic organisms and adversely affect the biodegradation process. The attachment was connected to the normally-closed butterfly valve and leachate portion installed into the bioreactor cap. Leachate was then added by clearing the apparatus of oxygen and opening up both butterfly valves. The handheld reader remained connected to the probe while additional leachate was added to ensure moisture content of above 45 percent was re-established. Once moisture was replenished, each valve was closed, and the leachate reservoir disconnected. As the environment and proportion of waste constituents within each bioreactor of a bioreactor set are identical, it is anticipated that each required similar volumes of additional leachate to achieve the recommended limits and the process was repeated for the bioreactor set. A schematic of the leachate injection is provided as Figure B.5.1.

Leachate was obtained from the Middlesex County Utilities Authority (MCUA) Middlesex County Landfill in East Brunswick, New Jersey. Chemical analyses conducted on the leachate have been provided under Figure B.5.2 – Leachate Chemical Analyses Test Results.

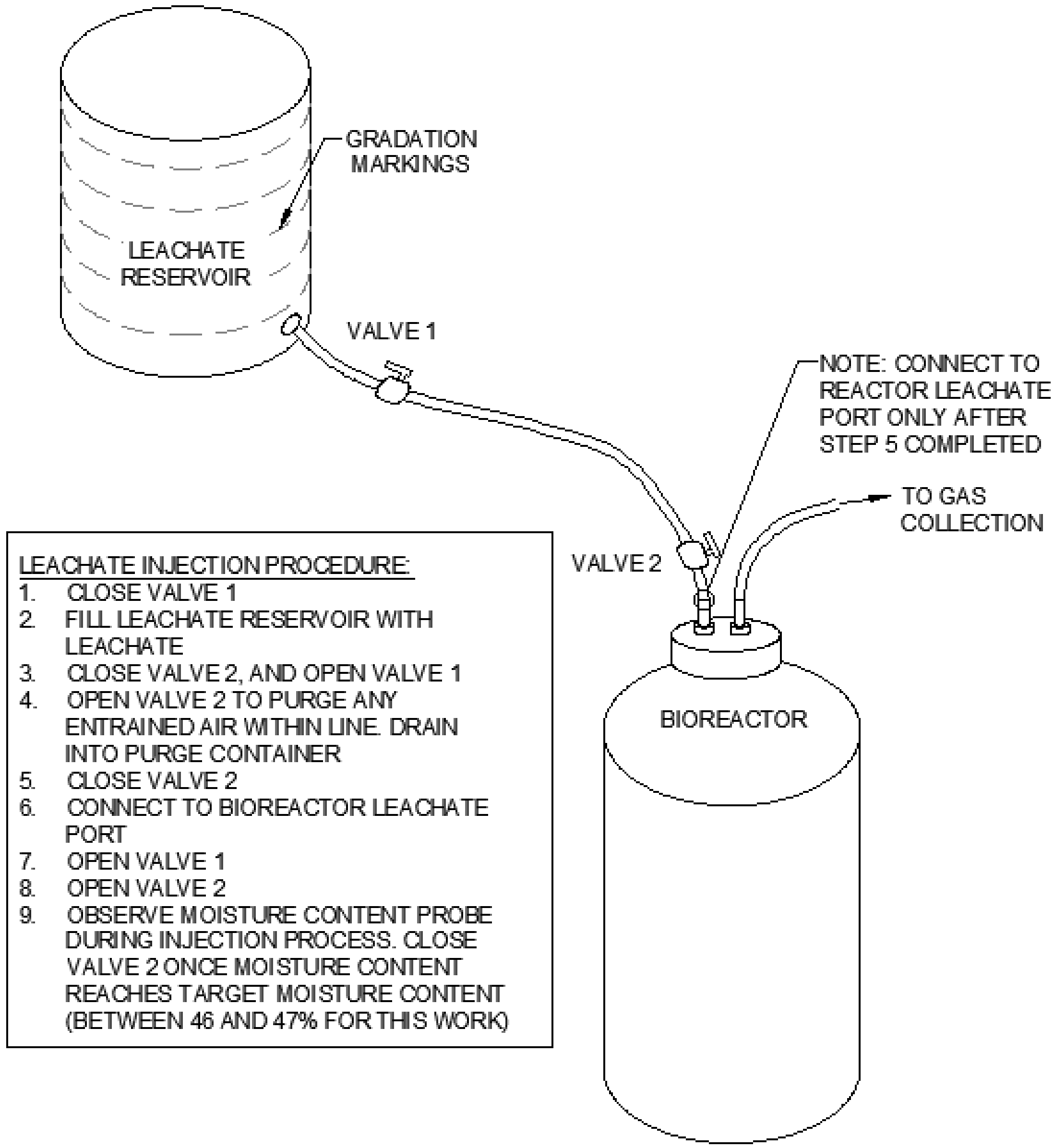

Figure B.5.1 Leachate Injection Procedure

Table B.5.1 Moisture Content Record for Composite Bioreactor Set

Date	Cum. Days	Samples Charged	Initial Moisture Content [%]	End Moisture Content [%]	Days Since Last Charge
11/18/13	0	C (16)	41.2	46.1	0
11/23/13	5	C (16)	39.3	46.3	5
11/24/13	6	C (16)	43.2	46.2	1
11/26/13	8	C (16)	41.9	46.0	2
11/29/13	11	C (16)	39.8	46.5	3
12/1/13	13	C (16)	42.1	46.5	2
12/3/13	15	C (16)	41.1	46.6	2
12/5/13	17	C (16)	40.6	46.7	2
12/6/13	18	C (16)	43.1	45.9	1
12/8/13	20	C (16)	41.5	46.3	2
12/12/13	24	C (16)	38.5	46.2	4
12/15/13	27	C (16)	40.1	45.9	3
12/18/13	30	C (16)	39.8	46.5	3
12/22/13	34	C (16)	38.7	47.1	4
12/25/13	37	C (16)	41.1	46.8	3
12/29/13	41	C (16)	39.6	46.9	4
12/31/13	43	C (16)	42.4	46.7	2
1/4/14	47	C (16)	38.6	46.5	4
1/11/14	54	C (15)	33.9	46.8	7
1/13/14	56	C (15)	42.1	46.5	2
1/18/14	61	C (15)	37.3	46.3	5
1/21/14	64	C (14)	40.9	46.2	3
1/24/14	67	C (14)	41.2	46.5	3
1/28/14	71	C (14)	39.3	46.4	4
1/31/14	74	C (14)	40.1	46.6	3

Table B.5.1 Moisture Content Record for Composite Bioreactor Set (continued)

Date	Cum. Days	Samples Charged	Initial Moisture Content [%]	End Moisture Content [%]	Days Since Last Charge
2/1/14	75	C (14)	46.2	46.8	1
2/4/14	78	C (14)	42.3	47.2	3
2/8/14	82	C (14)	39.3	46.3	4
2/11/14	85	C (14)	40.6	46.7	3
2/16/14	90	C (14)	37.4	46.2	5
2/19/14	93	C (13)	42.1	46.7	3
2/22/14	96	C (13)	43.2	45.9	3
2/26/14	100	C (13)	42.8	46.1	4
3/2/14	104	C (13)	39.6	46.8	4
3/5/14	107	C (13)	42.3	47.2	3
3/8/14	110	C (13)	42.9	47.1	3
3/16/14	118	C (13)	38.6	46.7	8
3/18/14	120	C (12)	43.6	46.9	2
3/21/14	123	C (12)	43.2	46.2	3
3/30/14	132	C (12)	38.4	46.1	9
4/5/14	138	C (12)	36.7	46.2	6
4/12/14	145	C (12)	36.6	46.3	7
4/19/14	152	C (12)	33.8	46.5	7
4/27/14	160	C (12)	42.2	46.7	8
5/10/14	173	C (12)	42.7	46.6	13
5/28/14	191	C (11)	42.4	46.2	18
6/13/14	207	C (11)	-	-	16

Table B.5.2 Moisture Content Record for Readily Degradable Bioreactor Set

Date	Days Since Start	Samples Charged	Initial Moisture Content [%]	End Moisture Content [%]	Interval Since Last Charge
11/18/13	0	R (6)	44.2	45.3	0
11/23/13	5	R (6)	36.6	46.2	5
11/24/13	6	R (6)	44.4	46.7	1
11/26/13	8	R (6)	38.4	47.1	2
11/29/13	11	R (6)	36.9	45.7	3
12/1/13	13	R (6)	39.5	45.9	2
12/3/13	15	R (6)	39.2	46.4	2
12/5/13	17	R (6)	37.6	45.9	2
12/6/13	18	R (6)	42.2	45.2	1
12/8/13	20	R (6)	40.4	47.1	2
12/12/13	24	R (6)	39.8	46.6	4
12/15/13	27	R (6)	38.7	45.9	3
12/18/13	30	R (6)	39.2	45.8	3
12/22/13	34	R (6)	40.2	45.6	4
12/25/13	37	R (6)	41.1	46.7	3
12/29/13	41	R (6)	41.6	45.6	4
12/31/13	43	R (6)	42.7	45.8	2
1/4/14	47	R (6)	42.7	46.7	4
1/11/14	54	R (6)	38.2	47.1	7
1/13/14	56	R (6)	43.2	46.8	2
1/18/14	61	R (6)	40.8	45.8	5
1/21/14	64	R (6)	40.7	46.1	3
1/24/14	67	R (6)	41.2	45.8	3
1/28/14	71	R (6)	41.1	46.1	4
1/31/14	74	R (6)	40.8	46.3	3

Table B.5.2 Moisture Content Record for Readily Deg. Bioreactor Set (continued)

Date	Days Since Start	Samples Charged	Initial Moisture Content [%]	End Moisture Content [%]	Interval Since Last Charge
2/1/14	75	R (6)	44.7	45.8	1
2/4/14	78	R (6)	43.1	47.1	3
2/8/14	82	R (6)	42.8	46.3	4
2/11/14	85	R (6)	42.2	45.8	3
2/16/14	90	R (6)	39.6	46.3	5
2/19/14	93	R (6)	41.4	45.2	3
2/22/14	96	R (6)	41.8	46.1	3
2/26/14	100	R (6)	40.7	45.6	4
3/2/14	104	R (6)	41.3	45.4	4
3/5/14	107	R (6)	44.4	46.6	3
3/8/14	110	R (6)	42.3	45.5	3
3/16/14	118	R (6)	39.9	45.8	8

Table B.5.3 Moisture Content Record for Moderately Deg. Bioreactor Set

Date	Days Since Start	Samples Charged	Initial Moisture Content [%]	End Moisture Content [%]	Interval Since Last Charge
11/18/13	0	M (6)	42.1	47.6	0
11/23/13	5	M (6)	41.1	48.2	5
11/24/13	6	M (6)	44.5	46.6	1
11/26/13	8	M (6)	42.2	46.5	2
11/29/13	11	M (6)	41.0	46.2	3
12/1/13	13	M (6)	43.4	47.1	2
12/3/13	15	M (6)	42.3	46.2	2
12/5/13	17	M (6)	41.2	46.3	2
12/6/13	18	M (6)	45.0	47.1	1
12/8/13	20	M (6)	42.3	46.8	2
12/12/13	24	M (6)	36.2	46.7	4
12/15/13	27	M (6)	38.1	46.3	3
12/18/13	30	M (6)	38.6	47.1	3
12/22/13	34	M (6)	36.2	46.8	4
12/25/13	37	M (6)	39.7	48.1	3
12/29/13	41	M (6)	34.6	45.9	4
12/31/13	43	M (6)	41.2	47.0	2
1/4/14	47	M (6)	34.5	46.3	4
1/11/14	54	M (6)	28.6	45.9	7
1/13/14	56	M (6)	39.2	46.3	2
1/18/14	61	M (6)	32.2	47.1	5
1/21/14	64	M (6)	36.5	47.2	3
1/24/14	67	M (6)	34.7	46.2	3
1/28/14	71	M (6)	34.1	45.9	4
1/31/14	74	M (6)	36.5	46.4	3
2/1/14	75	M (6)	44.3	46.8	1
2/4/14	78	M (6)	38.6	46.2	3

Table B.5.3 Moisture Content Record for Moderately Deg. Bioreactor Set (continued)

Date	Days Since Start	Samples Charged	Initial Moisture Content [%]	End Moisture Content [%]	Interval Since Last Charge
2/8/14	82	M (6)	35.6	46.5	4
2/11/14	85	M (6)	40.1	47.1	3
2/16/14	90	M (6)	36.5	45.9	5
2/19/14	93	M (6)	40.1	46.2	3
2/22/14	96	M (6)	39.6	45.8	3
2/26/14	100	M (6)	39.4	46.2	4
3/2/14	104	M (6)	38.6	45.9	4
3/5/14	107	M (6)	42.2	47.1	3
3/8/14	110	M (6)	41.8	46.6	3
3/16/14	118	M (6)	36.7	46.3	8
3/18/14	120	M (6)	43.8	46.3	2
3/21/14	123	M (6)	42.3	46.2	3
3/30/14	132	M (6)	36.7	45.9	9
4/5/14	138	M (6)	37.5	46.4	6
4/12/14	145	M (6)	36.5	46.2	7
4/19/14	152	M (6)	36.2	46.7	7
4/27/14	160	M (6)	37.9	46.3	8
5/10/14	173	M (6)	34.8	45.9	13
5/17/14	180	M (6)	38.4	46.3	7
5/28/14	191	M (6)	36.7	46.1	11
6/7/14	201	M (6)	35.9	46.4	10
6/13/14	207	M (6)	40.0	46.5	6
6/21/14	215	M (6)	40.7	46.2	8
6/28/14	222	M (6)	39.6	46.6	7
7/5/14	229	M (6)	40.6	45.9	7
7/13/14	237	M (6)	40.1	46.2	8
7/26/14	250	M (6)	41.3	46.4	13

Table B.5.4 Moisture Content Record for Slowly Deg. Bioreactor Set

Date	Days Since Start	Samples Charged	Initial Moisture Content [%]	End Moisture Content [%]	Interval Since Last Charge
11/18/13	0	S (6)	44.2	46.6	0
11/23/13	5	S (6)	44.3	46.8	5
11/24/13	6	S (6)	46.7	47.1	1
11/26/13	8	S (6)	44.6	46.3	2
11/29/13	11	S (6)	44.8	45.9	3
12/1/13	13	S (6)	44.2	46.2	2
12/3/13	15	S (6)	44.1	46.2	2
12/5/13	17	S (6)	43.8	46.6	2
12/6/13	18	S (6)	46.6	48.1	1
12/8/13	20	S (6)	44.3	47.6	2
12/12/13	24	S (6)	44.1	46.6	4
12/15/13	27	S (6)	44.6	45.9	3
12/18/13	30	S (6)	44.2	46.2	3
12/22/13	34	S (6)	44.3	46.3	4
12/25/13	37	S (6)	44.1	46.7	3
12/29/13	41	S (6)	44.3	46.2	4
12/31/13	43	S (6)	43.9	45.9	2
1/4/14	47	S (6)	43.7	45.8	4
1/11/14	54	S (6)	44.1	46.2	7
1/13/14	56	S (6)	44.2	46.4	2
1/18/14	61	S (6)	43.8	46.2	5
1/21/14	64	S (6)	44.1	45.9	3
1/24/14	67	S (6)	44.0	47.1	3
1/28/14	71	S (6)	41.2	46.4	4
1/31/14	74	S (6)	43.8	46.2	3
2/1/14	75	S (6)	46.0	47.6	1

Table B.5.4 Moisture Content Record for Slowly Deg. Bioreactor Set (continued)

Date	Days Since Start	Samples Charged	Initial Moisture Content [%]	End Moisture Content [%]	Interval Since Last Charge
2/4/14	78	S (6)	45.1	46.8	3
2/8/14	82	S (6)	44.8	47.1	4
2/11/14	85	S (6)	46.1	46.8	3
2/16/14	90	S (6)	43.1	45.9	5
2/19/14	93	S (6)	44.3	46.7	3
2/22/14	96	S (6)	44.1	46.3	3
2/26/14	100	S (6)	44.2	46.5	4
3/2/14	104	S (6)	44.1	47.1	4
3/5/14	107	S (6)	43.3	46.8	3
3/8/14	110	S (6)	44.1	46.7	3
3/16/14	118	S (6)	42.1	45.9	8
3/18/14	120	S (6)	44.6	46.3	2
3/21/14	123	S (6)	44.5	47.2	3
3/30/14	132	S (6)	41.1	47.1	9
4/5/14	138	S (6)	40.2	46.8	6
4/12/14	145	S (6)	41.1	46.7	7
4/19/14	152	S (6)	41.6	47.1	7
4/27/14	160	S (6)	42.8	47.6	8
5/10/14	173	S (6)	40.1	46.5	13
5/17/14	180	S (6)	43.4	46.8	7
5/28/14	191	S (6)	38.4	45.7	11
6/7/14	201	S (6)	42.1	46.2	10
6/13/14	207	S (6)	42.3	46.8	6
6/21/14	215	S (6)	45.0	47.2	8
6/28/14	222	S (6)	42.0	46.8	7
7/5/14	229	S (6)	43.1	47.2	7
7/13/14	237	S (6)	40.1	46.4	8
7/26/14	250	S (6)	41.3	46.7	13

Report of Analysis

Sample Location / Des. Middlesex County Landfill Leachate Collection
Sample Number: PS 3
Date Sampled: 9/17/13
Date Reported: 9/23/13

Parameter	Result	Units	MDL 2013	Method	Date of Analysis
*pH	7.38	s.u.	----------	SM 4500 H+B	9/17/13
SPECIFIC CONDUCTANCE (UMHOS)	2770	UMHO's/CM	----------	SM 2510B	9/20/13
COD	2930	mg/l	86.8	HACH 8000	9/18/13
CHLORIDE	10700	mg/l	98.6	SM 4500 Cl-B	9/20/13
*TEMPERATURE	17.0	°C	----------	SM 2550 B	9/17/13

Figure B.5.2 Leachate Chemical Analyses Test Results

Sample Location /Des. Middlesex County Landfill Leachate Collection
Sample Number: PS 3
Date Sampled: 3/15/13
Date Reported: 3/29/13

Parameter	Result	Units	MDL 2013	Method	Date of Analysis
*pH	7.01	-----------	----------	4500H+B	3/15/13
SPECIFIC CONDUCTANCE (UMHOS)	18028	UMHO'S/CM	----------	2510B	3/16/13
COD	2230	mg/l	86.8	HACH8000	3/15/13
CHLORIDE	1460	mg/l	98.6	4500CI-B	3/18/13
*TEMPERATURE	20.0	°C	---------	2550B	3/15/13

Figure B.5.3 Leachate Chemical Analyses Test Results (continued)

Report of Analysis

Sample Location / Des. Middlesex County Landfill Leachate Collection
Sample Number: PS 3
Date Sampled: 6/19/13
Date Reported: 6/24/13

Parameter	Result	Units	MDL 2013	Method	Date of Analysis
*pH	7.42	s.u.	----------	SM 4500 H+B	6/19/13
SPECIFIC CONDUCTANCE (UMHOS)	14500	UMHO's/CM	----------	SM 2510B	6/21/13
COD	3930	mg/l	86.8	HACH 8000	6/20/13
CHLORIDE	1980	mg/l	98.6	SM 4500 Cl-B	6/21/13
*TEMPERATURE	18.0	°C	----------	SM 2550 B	6/19/13

Figure B.5.4 Leachate Chemical Analyses Test Results (continued)

B.6 (C+H)/L Test Record

Bioreactors decommissioned to test for compression testing were subsequently sampled and sent for (C+H)/L testing to determine the state of biodegradation of the waste. Samples were sent to Dr. Morton A. Barlaz at North Carolina State University for (C+H)/L testing. As discussed in Chapter 4, prior to submission for testing, samples were processed by removing plastics and synthetics from the sample. These constituents were removed as it was shown plastic and synthetic constituents do not dissolve in a 72 percent weight by weight (w/w) solution of sulfuric acid.

Table B.6.1 includes the data maintained by the author during the experiment phase. Table B.6.2 through B.6.4 represent the as-received test results from Dr. Barlaz indicating cellulose, hemicellulose, lignin and biodegradable solids as percent of the waste mass. Two tests were completed for each sample and an average presented of the test results. A Relative Percent Deviation, defined as the standard deviation divided by the average (reported in percent) is presented to quantify precision of the test. A low Relative Percent Deviation would indicate lower variability of the test data, while a higher percentage would indicate the data is more varied. Sample results obtained from this work were observed to have low Relative Percent Deviation.

Table B.6.1 Records Maintained for Cellulose + Hemicellulose over Lignin Tests

Sample Number	Date Removed	Removed From Bioreactor Number	Total Amount of Sample Removed [g]	Sample Sent to Barlaz [lb]	Waste Removed from Bioreactor, Dry [lb]	Date Sent to Barlaz	Date Tested
C-INITIAL-1	INITIAL	INITIAL	264	264	-	12/26/13	2/6/14
C-INITIAL-2	INITIAL	INITIAL	198	264	-	12/26/13	2/6/14
R-INITIAL-1	INITIAL	INITIAL	248	106	-	12/26/13	2/6/14
R-INITIAL-2	INITIAL	INITIAL	276	146	-	12/26/13	2/6/14
M-INITIAL-1	INITIAL	INITIAL	194	487	-	12/26/13	2/6/14
M-INITIAL-2	INITIAL	INITIAL	198	189	-	12/26/13	2/6/14
C-1-1	1/6/14	C-1	775.6	49.6	775.6	1/16/14	3/18/14
C-1-2	1/6/14	C-1	775.6	51.8	775.6	1/16/14	3/18/14
C-2-1	1/19/14	C-2	780.2	48.8	780.2	1/25/14	3/26/14
C-2-2	1/19/14	C-2	780.2	51.4	780.2	1/25/14	3/26/14
C-3-1	2/19/14	C-3	775.0	55.4	775.0	2/24/14	4/6/14
C-3-2	2/19/14	C-3	775.0	56.8	775.0	2/24/14	4/6/14
C-4-1	3/20/14	C-4	784.0	61.3	784.0	3/23/14	5/2/14
C-4-2	3/20/14	C-4	784.0	52.1	784.0	3/23/14	5/2/14
C-4-3	3/20/14	C-4	784.0	48.1	784.0	3/23/14	5/2/14
C-4-4	3/20/14	C-4	784.0	51.1	784.0	3/23/14	5/2/14
C-INITIAL-RETEST-1	9/2/14	NEW	324	324	-	9/6/14	10/5/14
C-INITIAL-RETEST-2	9/2/14	NEW	317	317	-	9/6/14	10/5/14

Table B.6.2 Results for Cellulose + Hemicellulose over Lignin Tests

		% Cellulose (C)				% Hemicellulose (H)			
NCSU Lab #	Sample ID	Rep 1	Rep 2	Avg.	RPD	Rep 1	Rep 2	Avg.	RPD
14-1	C-Initial-1	44.96	51.54	48.25	9.6%	9.15	10.14	9.65	7.3%
14-2	C-Initial-2	43.42	42.72	43.07	1.1%	9.88	8.89	9.39	7.5%
14-3	R-Initial-1	47.22	53.06	50.14	8.2%	5.23	5.87	5.55	8.2%
14-4	R-Initial-2	55.02	53.67	54.35	1.8%	4.45	4.51	4.48	0.9%
14-5	M-Initial-1	40.90	39.76	40.33	2.0%	10.19	10.75	10.47	3.8%
14-6	M-Initial-2	51.51	47.67	49.59	5.5%	11.76	10.58	11.17	7.5%
14-7	C-1-1	10.41	8.37	9.39	15.4%	4.90	3.72	4.31	19.4%
14-8	C-1-2	14.43	9.43	11.93	29.6%	6.34	4.68	5.51	21.3%
14-9	C-2-1	19.55	18.72	19.14	3.1%	5.99	5.78	5.89	2.5%
14-10	C-2-2	15.76	14.14	14.95	7.7%	6.62	5.68	6.15	10.8%
14-24	C-3-1	11.48	10.79	11.14	4.4%	4.73	4.13	4.43	9.6%
14-25	C-3-2	8.61	9.11	8.86	4.0%	3.53	3.95	3.74	7.9%
14-37	C-4-1 (Plastics, synthetics removed)	7.08	7.30	7.19	2.2%	2.43	1.82	2.13	20.3%
14-38	C-4-2 (Plastics, synthetics removed)	7.36	6.63	7.00	7.4%	2.42	1.78	2.10	21.5%
14-39	C-4-3 (Unprocessed)	5.43	5.20	5.32	3.1%	2.31	2.78	2.55	13.1%
14-40	C-4-4 (Unprocessed)	6.45	4.60	5.53	23.7%	2.78	1.81	2.30	29.9%
14-356	C-Initial retest-1 (Plastics, synthetics removed)	51.26	39.45	45.36	18.4%	7.98	6.38	7.18	15.8%
14-357	C-Initial retest-2 (Plastics, synthetics removed)	44.18	44.66	44.42	0.8%	6.40	7.08	6.74	7.1%

Table B.6.3 Results for Cellulose + Hemicellulose over Lignin Tests (Continued)

		% Lignin (L)				% Lipophillic Extractives			
NCSU Lab #	Sample ID	Rep 1	Rep 2	Avg.	RPD	Rep 1	Rep 2	Avg.	RPD
14-1	C-Initial-1	4.70	4.42	4.56	4.3%	-2.43	-2.14	-2.29	-9.0%
14-2	C-Initial-2	4.77	5.04	4.91	3.9%	-3.28	-3.33	-3.31	-1.1%
14-3	R-Initial-1	6.02	5.51	5.77	6.3%	-1.99	-2.08	-2.04	-3.1%
14-4	R-Initial-2	5.27	5.42	5.35	2.0%	-2.01	-2.10	-2.06	-3.1%
14-5	M-Initial-1	3.87	4.13	4.00	4.6%	-3.65	-3.51	-3.58	-2.8%
14-6	M-Initial-2	4.37	4.46	4.42	1.4%	-3.53	-3.53	-3.53	0.0%
14-7	C-1-1	21.94	21.75	21.85	0.6%	-0.47	-0.50	-0.49	-4.4%
14-8	C-1-2	22.30	21.63	21.97	2.2%	-0.35	-0.12	-0.24	-69.2%
14-9	C-2-1	25.81	25.19	25.50	1.7%	-1.30	-1.24	-1.27	-3.3%
14-10	C-2-2	26.80	27.08	26.94	0.7%	-1.49	-1.11	-1.30	-20.7%
14-24	C-3-1	24.67	23.67	24.17	2.9%	1.28	1.18	1.23	5.7%
14-25	C-3-2	20.85	22.01	21.43	3.8%	1.48	1.61	1.55	5.9%
14-37	C-4-1 (Plastics, synthetics removed)	20.72	22.11	21.42	4.6%	1.35	1.40	1.38	2.6%
14-38	C-4-2 (Plastics, synthetics removed)	20.92	20.69	20.81	0.8%	0.94	0.94	0.94	0.0%
14-39	C-4-3 (Unprocessed)	31.84	30.50	31.17	3.0%	1.17	0.97	1.07	13.2%
14-40	C-4-4 (Unprocessed)	33.62	40.15	36.89	12.5%	0.86	0.85	0.86	0.8%
14-356	C-Initial retest-1 (Plastics, synthetics removed)	5.09	5.37	5.23	3.8%	4.90	4.65	4.78	3.7%
14-357	C-Initial retest-2 (Plastics, synthetics removed)	13.89	14.27	14.08	1.9%	3.95	4.02	3.99	1.2%

Table B.6.4 Results for Cellulose + Hemicellulose over Lignin Tests (Continued)

		% Organic Solids				(C+H) / L	C+H+L+Extr / VS
NCSU Lab #	Sample ID	Rep 1	Rep 2	Avg.	RPD ±25%	From averages	From averages (%)
14-1	C-Initial-1	78.5	79.6	79.05	1.0%	12.70	0.76
14-2	C-Initial-2	80.4	80.7	80.55	0.3%	10.69	0.67
14-3	R-Initial-1	97.6	97.5	97.55	0.1%	9.66	0.61
14-4	R-Initial-2	97.3	97.3	97.30	0.0%	11.01	0.64
14-5	M-Initial-1	78.0	78.0	78.00	0.0%	12.70	0.66
14-6	M-Initial-2	77.4	77.6	77.50	0.2%	13.76	0.80
14-7	C-1-1	52.5	53.1	52.80	0.8%	0.63	0.66
14-8	C-1-2	52.0	52.0	52.00	0.0%	0.79	0.75
14-9	C-2-1	66.4	65.8	66.10	0.6%	0.98	0.75
14-10	C-2-2	56.1	58.1	57.10	2.5%	0.78	0.82
14-24	C-3-1	50.8	51.5	51.15	1.0%	0.64	0.80
14-25	C-3-2	48.4	47.7	48.05	1.0%	0.59	0.74
14-37	C-4-1 (Plastics, synthetics removed)	47.4	48.2	47.80	1.2%	0.43	0.67
14-38	C-4-2 (Plastics, synthetics removed)	45.1	43.6	44.35	2.4%	0.44	0.70
14-39	C-4-3 (Unprocessed)	39.4	38.8	39.10	1.1%	0.25	1.03
14-40	C-4-4 (Unprocessed)	41.4	43.8	42.60	4.0%	0.21	1.07
14-356	C-Initial retest-1 (Plastics, synthetics removed)	72.5	74.1	73.30	1.5%	10.04	0.85
14-357	C-Initial retest-2 (Plastics, synthetics removed)	76.1	77.5	76.80	1.3%	3.63	0.90

B.7 End of Test Bioreactor Decommissioning Records

Following completion of the experiment, remaining operational bioreactors were decommissioned after undergoing a series of measurements. The intent of the measurements was to understand the loss of biodegradable mass attributable to decomposition, compute percent biodegradation of the sample based on weight, observe any change in density of the waste sample, and verify moisture content of the bioreactor.

Generally, the decommissioning process consisted of saw-cutting the top of the bioreactor jar to expose the waste. The height of the sample was measured using a ruler with one-tenth inch markings to determine final density. Subsequently, the waste was removed from each bioreactor and placed into individual pans for measuring wet weight. The samples were oven-dried at low heat at 110°F to avoid burn-off of organic fractions, and the dry weight of the waste was computed to determine moisture content of the sample. Using bioreactor commissioning records at the start of the experiment, the original weight of biodegradable and non-biodegradable constituents was known thereby allowing for a computation of the remaining weight of biodegradable fraction and percent biodegraded at the end of the experiment.

It is noted that each bioreactor jar was 7.44 inches in diameter, equating to a cross sectional area of 43.47 square inches, or 0.30 square feet, which was used to computer density of the waste sample. A conversion factor of 453.59 grams to 1 pound was used for calculations. Initial weights which are listed are provided in commissioning records in Appendix A.

Table B.7.1 End of Bioreactor Decommissioning Records - Composite

Sample Jar No.	Pan Weight [g]	Pan + Wet Sample Weight [g]	Wet Sample Weight [g]	Pan + Dry Sample Weight [g]	Dry Sample Weight [g]	Wwater [g]	End Moisture Content [%]	Final Height of Sample [in]
C-7	104.77	702.17	597.4	515.64	410.87	186.53	45.40%	1.40
C-8	101.35	711.78	610.43	518.39	417.04	193.39	46.37%	1.50
C-9	102.47	714.8	612.33	517.64	415.17	197.16	47.49%	1.50
C-10	102.54	718.48	615.94	521.86	419.32	196.62	46.89%	1.40
C-11	101.42	691.93	590.51	507.07	405.65	184.86	45.57%	1.40
C-12	101.63	701.57	599.94	510.64	409.01	190.93	46.68%	1.40
C-13	100.74	714.86	614.12	518.82	418.08	196.04	46.89%	1.50
C-14	103.41	713.17	609.76	512.37	408.96	200.8	49.10%	1.40
C-15	102.88	707.19	604.31	512.17	409.29	195.02	47.65%	1.40
C-16	103.74	693.27	589.53	503.1	399.36	190.17	47.62%	1.40

Table B.7.2 End of Bioreactor Decommissioning Records – Composite (continued)

Sample Jar No.	Total End Wet Sample Weight [lb]	Total End Dry Sample Weight [lb]	Final Density [lb/ft3]	Change in Density [%]	Total End Biodegradable Weight Remaining [lb]	Weight Lost [lb]	Original Weight of Degradable Constituents [lb]	% Biodegraded
C-7	1.32	0.91	37.39	91.33%	0.50	1.19	1.69	71%
C-8	1.35	0.92	35.66	86.73%	0.51	1.18	1.69	70%
C-9	1.35	0.92	35.77	87.75%	0.52	1.18	1.70	70%
C-10	1.36	0.92	38.55	93.96%	0.51	1.18	1.69	70%
C-11	1.30	0.89	36.96	90.48%	0.49	1.21	1.70	71%
C-12	1.32	0.90	37.55	92.12%	0.49	1.20	1.69	71%
C-13	1.35	0.92	35.88	88.78%	0.51	1.18	1.69	70%
C-14	1.34	0.90	38.17	94.24%	0.49	1.20	1.69	71%
C-15	1.33	0.90	37.82	93.40%	0.49	1.20	1.69	71%
C-16	1.30	0.88	36.90	91.32%	0.47	1.22	1.69	72%

Table B.7.3 End of Bioreactor Decommissioning Records – Readily Degradable

Sample Jar No.	Pan Weight [g]	Pan + Wet Sample Weight [g]	Wet Sample Weight [g]	Pan + Dry Sample Weight [g]	Dry Sample Weight [g]	Water [g]	End Moisture Content [%]	Final Height of Sample [in]
R-1	94.51	228.56	134.05	186.83	92.32	41.73	45.20%	0.40
R-2	95.52	236.61	141.09	190.45	94.93	46.16	48.63%	0.30
R-3	94.29	226.44	132.15	184	89.71	42.44	47.31%	0.30
R-4	104.86	245.35	140.49	200.66	95.8	44.69	46.65%	0.30
R-5	101.42	240.28	138.86	194.61	93.19	45.67	49.01%	0.30
R-6	103.99	239.01	135.02	195.44	91.45	43.57	47.64%	0.30

Table B.7.4 End of Bioreactor Decommissioning Records – Readily Deg. (continued)

Sample Jar No.	Total End Wet Sample Weight [lb]	Total End Dry Sample Weight [lb]	Final Density [lb/ft3]	Change in Density [%]	Total End Biodegradable Weight Remaining [lb]	Weight Lost [lb]	Original Weight of Degradable Constituents [lb]	% Biodegraded
R-1	0.30	0.20	29.37	72.04%	0.20	1.90	2.10	90%
R-2	0.31	0.21	41.21	90.30%	0.21	1.89	2.10	90%
R-3	0.29	0.20	38.60	80.52%	0.20	1.90	2.10	91%
R-4	0.31	0.21	41.04	88.37%	0.21	1.89	2.10	90%
R-5	0.31	0.21	40.56	83.83%	0.21	1.89	2.10	90%
R-6	0.30	0.20	39.44	85.59%	0.20	1.90	2.10	90%

Table B.7.5 End of Bioreactor Decommissioning Records – Moderately Degradable

Sample Jar No.	Pan Weight [g]	Pan + Wet Sample Weight [g]	Wet Sample Weight [g]	Pan + Dry Sample Weight [g]	Dry Sample Weight [g]	Water [g]	End Moisture Content [%]	Final Height of Sample [in]
M-1	102.52	555.47	452.95	411.97	309.45	143.5	46.37 %	1.00
M-2	102.55	535.52	432.97	401.69	299.14	133.83	44.74 %	0.90
M-3	104.9	601.69	496.79	444.52	339.62	157.17	46.28 %	1.00
M-4	99.86	543.93	444.07	401.31	301.45	142.62	47.31 %	0.90
M-5	99.84	542.09	442.25	397.23	297.39	144.86	48.71 %	0.90
M-6	102.75	589.29	486.54	435.22	332.47	154.07	46.34 %	1.00

Table B.7.6 End of Bioreactor Decommissioning Records – Moderately Deg. (continued)

Sample Jar No.	Total End Wet Sample Weight [lb]	Total End Dry Sample Weight [lb]	Final Density [lb/ft3]	Change in Density [%]	Total End Biodegradable Weight Remaining [lb]	Weight Lost [lb]	Original Weight of Degradable Constituents [lb]	% Biodegraded
M-1	1.00	0.68	39.69	85.31 %	0.68	1.42	2.10	68%
M-2	0.95	0.66	42.16	90.61 %	0.66	1.44	2.10	69%
M-3	1.10	0.75	43.53	93.57 %	0.75	1.35	2.10	64%
M-4	0.98	0.66	43.24	95.11 %	0.66	1.44	2.10	68%
M-5	0.97	0.66	43.06	92.55 %	0.66	1.44	2.10	69%
M-6	1.07	0.73	42.63	91.64 %	0.73	1.37	2.10	65%

Table B.7.7 End of Bioreactor Decommissioning Records – Slowly Degradable

Sample Jar No.	Pan Weight [g]	Pan + Wet Sample Weight [g]	Wet Sample Weight [g]	Pan + Dry Sample Weight [g]	Dry Sample Weight [g]	Water [g]	End Moisture Content [%]	Final Height of Sample [in]
S-1	100.75	1997.4 8	1896.73	1374.41	1273.66	623.0 7	48.92 %	4.30
S-2	103.45	1994.6 9	1891.24	1363.94	1260.49	630.7 5	50.04 %	4.40
S-3	104.82	14.34	1909.52	1401.7	1296.88	612.6 4	47.24 %	4.50
S-4	104.32	1964.7 1	1860.39	1371.27	1266.95	593.4 4	46.84 %	4.30
S-5	101.25	1998.4 8	1897.23	1368.02	1266.77	630.4 6	49.77 %	4.20
S-6	103.42	2012.4 9	1909.07	1385.45	1282.03	627.0 4	48.91 %	4.40

Table B.7.8 End of Bioreactor Decommissioning Records – Slowly Deg. (continued)

Sample Jar No.	Total End Wet Sample Weight [lb]	Total End Dry Sample Weight [lb]	Final Density [lb/ft3]	Change in Density [%]	Total End Biodegradable Weight Remaining [lb]	Weight Lost [lb]	Original Weight of Degradable Constituents [lb]	% Biodegraded
S-1	4.18	2.81	38.65	98.02%	1.99	0.11	2.10	5%
S-2	4.17	2.78	37.66	96.16%	1.97	0.13	2.10	6%
S-3	4.21	2.86	37.18	97.58%	2.04	0.06	2.10	3%
S-4	4.10	2.79	37.91	97.23%	1.98	0.12	2.10	6%
S-5	4.18	2.79	39.58	98.39%	1.99	0.11	2.10	5%
S-6	4.21	2.83	38.02	97.07%	2.01	0.09	2.10	4%

APPENDIX C

CONSOLIDATION TEST RESULTS

Appendix C contains data and records collected throughout the course of the experiment. Samples were prepared for compression testing by mixing each waste to ensure uniform moisture content, then filling the sample within the consolidometer ring in lifts. Lifts were placed in approximately 1/4 inch loose lifts (approximately one tablespoon per lift) and were tamp-compacted using a hard rubber stopper with a 2.45 inch diameter placed on the sample and struck seven times with a 3.5 lb cylindrical weight dropped from a height of approximately one inch. This procedure was repeated until a final compacted height of one inch was obtained. Minor cosmetic trimming and patching was completed to create a uniform and flat sample surface for testing (Lifrieri 2010).

After compaction, samples were subsequently placed in a fixed ring consolidation cell manufactured by Humboldt and were tested using table-top mounted dead-weight consolidation equipment. Samples were allowed to consolidate at various pressures for a minimum period of two months or until it was observed that sample reached the stage of biodegradation, characterized by an increase in the strain rate (C_β). Dial gage reading data was recorded electronically at pre-determined time intervals using Humboldt HTMS logging software. Compression tests were performed in general accordance with ASTM D2435 – Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading (ASTM 2011). Samples were placed into the consolidometer and removed in accordance with the schedule shown in Table 4.5.

Load parameters for the samples to simulate self-weight and applied loads of landfills of variable heights were computed from resulting data. Compression parameters (C'_c, C_α, and C_β) were determined at the specific states of decomposition observed from testing. Records from initial and final compression tests are provided under Appendix C – Consolidation Test Results.

Twelve consolidation tests were completed during the course of the experiment. The author has provided start of biodegradation (C-1-1) test results as Table C.1 and end of experiment (C-FINAL-1) test results as Table C.2.

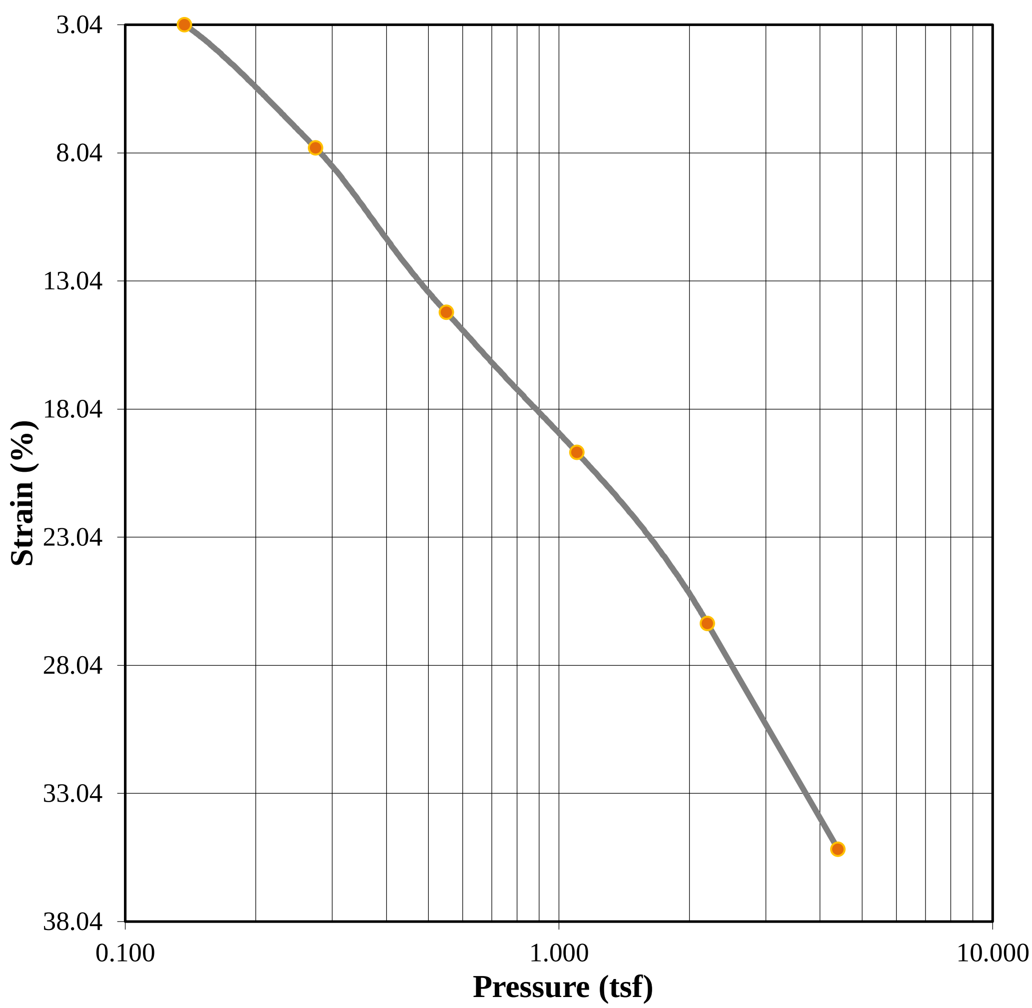

Figure C.1.1 Start of Biodegradation Strain versus Pressure Plot

Table C.1.1 Start of Biodegradation Waste Sample – 0.137 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.0002	0.0000	0.0000
1	00:00:01	0.0018	0.0016	0.1600
2	00:00:02	0.0022	0.0020	0.2000
3	00:00:03	0.0024	0.0022	0.2200
4	00:00:04	0.0026	0.0024	0.2400
5	00:00:05	0.0028	0.0026	0.2600
6	00:00:06	0.0030	0.0028	0.2800
7	00:00:12	0.0039	0.0037	0.3700
8	00:00:15	0.0043	0.0041	0.4100
9	00:00:30	0.0060	0.0058	0.5800
10	00:01:00	0.0084	0.0082	0.8200
11	00:02:00	0.0114	0.0112	1.1200
12	00:05:01	0.0153	0.0151	1.5100
13	00:10:01	0.0176	0.0174	1.7400
14	00:20:02	0.0193	0.0191	1.9100
15	00:40:04	0.0212	0.0210	2.1000
16	01:00:05	0.0219	0.0217	2.1700
17	02:00:11	0.0233	0.0231	2.3100
18	04:00:21	0.0255	0.0253	2.5300
19	08:00:43	0.0279	0.0277	2.7700
20	12:01:05	0.0290	0.0288	2.8800
21	16:01:26	0.0299	0.0297	2.9700
22	20:01:48	0.0306	0.0304	3.0400
23	20:25:14	0.0306	0.0304	3.0400

Table C.1.2 Start of Biodegradation Waste Sample – 0.275 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.0306	0.0304	3.0400
1	00:00:01	0.0333	0.0331	3.3100
2	00:00:02	0.0337	0.0335	3.3500
3	00:00:03	0.0341	0.0339	3.3900
4	00:00:04	0.0344	0.0342	3.4200
5	00:00:05	0.0347	0.0345	3.4500
6	00:00:06	0.0350	0.0348	3.4800
7	00:00:12	0.0364	0.0362	3.6200
8	00:00:15	0.0371	0.0369	3.6900
9	00:00:30	0.0399	0.0397	3.9700
10	00:01:00	0.0445	0.0443	4.4300
11	00:02:00	0.0506	0.0504	5.0400
12	00:05:00	0.0595	0.0593	5.9300
13	00:10:00	0.0642	0.0640	6.4000
14	00:20:01	0.0672	0.0670	6.7000
15	00:40:03	0.0691	0.0689	6.8900
16	01:00:05	0.0710	0.0708	7.0800
17	02:00:10	0.0727	0.0725	7.2500
18	04:00:21	0.0737	0.0735	7.3500
19	08:00:42	0.0750	0.0748	7.4800
20	12:01:05	0.0763	0.0761	7.6100
21	16:01:27	0.0776	0.0774	7.7400
22	20:01:48	0.0783	0.0781	7.8100
23	24:00:56	0.0787	0.0785	7.8500

Table C.1.3 Start of Biodegradation Waste Sample – 0.550 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.0787	0.0785	7.8500
1	00:00:01	0.0820	0.0818	8.1800
2	00:00:02	0.0826	0.0824	8.2400
3	00:00:03	0.0830	0.0828	8.2800
4	00:00:04	0.0832	0.0830	8.3000
5	00:00:05	0.0835	0.0833	8.3300
6	00:00:06	0.0837	0.0835	8.3500
7	00:00:12	0.0851	0.0849	8.4900
8	00:00:15	0.0856	0.0854	8.5400
9	00:00:30	0.0885	0.0883	8.8300
10	00:01:00	0.0915	0.0913	9.1300
11	00:02:00	0.0965	0.0963	9.6300
12	00:05:00	0.1070	0.1068	10.6800
13	00:10:01	0.1152	0.1150	11.5000
14	00:20:02	0.1216	0.1214	12.1400
15	00:40:04	0.1264	0.1262	12.6200
16	01:00:05	0.1282	0.1280	12.8000
17	02:00:11	0.1309	0.1307	13.0700
18	04:00:22	0.1335	0.1333	13.3300
19	08:00:43	0.1359	0.1357	13.5700
20	12:01:05	0.1374	0.1372	13.7200
21	16:01:27	0.1394	0.1392	13.9200
22	20:01:49	0.1411	0.1409	14.0900
23	24:02:11	0.1426	0.1424	14.2400
24	24:40:56	0.1428	0.1426	14.2600

Table C.1.4 Start of Biodegradation Waste Sample – 1.100 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.1428	0.1426	14.2600
1	00:00:01	0.1481	0.1479	14.7900
2	00:00:02	0.1487	0.1485	14.8500
3	00:00:03	0.1492	0.1490	14.9000
4	00:00:04	0.1495	0.1493	14.9300
5	00:00:05	0.1500	0.1498	14.9800
6	00:00:06	0.1504	0.1502	15.0200
7	00:00:12	0.1518	0.1516	15.1600
8	00:00:15	0.1523	0.1521	15.2100
9	00:00:30	0.1552	0.1550	15.5000
10	00:01:00	0.1589	0.1587	15.8700
11	00:02:00	0.1638	0.1636	16.3600
12	00:05:00	0.1704	0.1702	17.0200
13	00:10:01	0.1751	0.1749	17.4900
14	00:20:01	0.1792	0.1790	17.9000
15	00:40:03	0.1822	0.1820	18.2000
16	01:00:05	0.1840	0.1838	18.3800
17	02:00:11	0.1869	0.1867	18.6700
18	04:00:22	0.1890	0.1888	18.8800
19	08:00:44	0.1913	0.1911	19.1100
20	12:01:05	0.1921	0.1919	19.1900
21	16:01:26	0.1932	0.1930	19.3000
22	20:01:48	0.1945	0.1943	19.4300
23	24:02:10	0.1956	0.1954	19.5400
24	28:02:32	0.1961	0.1959	19.5900
25	32:02:54	0.1967	0.1965	19.6500
26	36:03:16	0.1971	0.1969	19.6900
27	39:48:01	0.1975	0.1973	19.7300

Table C.1.5 Start of Biodegradation Waste Sample – 2.200 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.1975	0.1973	19.7300
1	00:00:01	0.2047	0.2045	20.4500
2	00:00:02	0.2055	0.2053	20.5300
3	00:00:03	0.2061	0.2059	20.5900
4	00:00:04	0.2064	0.2062	20.6200
5	00:00:05	0.2068	0.2066	20.6600
6	00:00:06	0.2071	0.2069	20.6900
7	00:00:12	0.2086	0.2084	20.8400
8	00:00:15	0.2094	0.2092	20.9200
9	00:00:30	0.2119	0.2117	21.1700
10	00:01:00	0.2159	0.2157	21.5700
11	00:02:00	0.2207	0.2205	22.0500
12	00:05:00	0.2282	0.2280	22.8000
13	00:10:01	0.2341	0.2339	23.3900
14	00:20:02	0.2388	0.2386	23.8600
15	00:40:04	0.2431	0.2429	24.2900
16	01:00:05	0.2453	0.2451	24.5100
17	02:00:11	0.2492	0.2490	24.9000
18	04:00:22	0.2534	0.2532	25.3200
19	08:00:44	0.2575	0.2573	25.7300
20	12:01:06	0.2589	0.2587	25.8700
21	16:01:28	0.2596	0.2594	25.9400
22	20:01:49	0.2602	0.2600	26.0000
23	24:02:11	0.2609	0.2607	26.0700
24	28:02:33	0.2619	0.2617	26.1700
25	32:02:55	0.2630	0.2628	26.2800
26	36:03:17	0.2638	0.2636	26.3600
27	40:03:39	0.2641	0.2639	26.3900
28	43:17:35	0.2643	0.2641	26.4100

Table C.1.6 Start of Biodegradation Waste Sample – 4.400 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.2643	0.2641	26.4100
1	00:00:01	0.2735	0.2733	27.3300
2	00:00:02	0.2746	0.2744	27.4400
3	00:00:03	0.2752	0.2750	27.5000
4	00:00:04	0.2757	0.2755	27.5500
5	00:00:05	0.2761	0.2759	27.5900
6	00:00:06	0.2765	0.2763	27.6300
7	00:00:12	0.2778	0.2776	27.7600
8	00:00:15	0.2783	0.2781	27.8100
9	00:00:30	0.2803	0.2801	28.0100
10	00:01:00	0.2831	0.2829	28.2900
11	00:02:01	0.2865	0.2863	28.6300
12	00:05:01	0.2917	0.2915	29.1500
13	00:10:01	0.2960	0.2958	29.5800
14	00:20:02	0.2998	0.2996	29.9600
15	00:40:04	0.3033	0.3031	30.3100
16	01:00:06	0.3055	0.3053	30.5300
17	02:00:11	0.3090	0.3088	30.8800
18	04:00:23	0.3128	0.3126	31.2600
19	08:00:45	0.3183	0.3181	31.8100
20	12:01:06	0.3211	0.3209	32.0900
21	16:01:27	0.3225	0.3223	32.2300
22	20:01:49	0.3231	0.3229	32.2900
23	24:02:11	0.3236	0.3234	32.3400
24	28:02:33	0.3241	0.3239	32.3900
25	32:02:55	0.3251	0.3249	32.4900
26	36:03:17	0.3260	0.3258	32.5800
27	40:03:39	0.3265	0.3263	32.6300
28	44:04:01	0.3268	0.3266	32.6600
29	48:04:21	0.3270	0.3268	32.6800
30	52:04:43	0.3271	0.3269	32.6900
31	56:05:05	0.3274	0.3272	32.7200
32	60:05:27	0.3278	0.3276	32.7600
33	64:05:49	0.3279	0.3277	32.7700
34	68:06:11	0.3281	0.3279	32.7900
35	72:06:33	0.3283	0.3281	32.8100

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

36	76:06:55	0.3285	0.3283	32.8300
37	80:07:17	0.3287	0.3285	32.8500
38	84:07:38	0.3290	0.3288	32.8800
39	88:08:00	0.3291	0.3289	32.8900
40	92:08:23	0.3292	0.3290	32.9000
41	96:08:44	0.3294	0.3292	32.9200
42	100:09:0	0.3295	0.3293	32.9300
43	104:09:2	0.3298	0.3296	32.9600
44	108:09:2	0.3301	0.3299	32.9900
45	112:09:2	0.3303	0.3301	33.0100
46	116:09:2	0.3304	0.3302	33.0200
47	120:09:2	0.3305	0.3303	33.0300
48	124:09:2	0.3307	0.3305	33.0500
49	128:09:2	0.3310	0.3308	33.0800
50	132:09:2	0.3312	0.3310	33.1000
51	136:09:2	0.3313	0.3311	33.1100
52	140:09:2	0.3314	0.3312	33.1200
53	144:09:2	0.3315	0.3313	33.1300
54	148:09:2	0.3316	0.3314	33.1400
55	152:09:2	0.3317	0.3315	33.1500
56	156:09:2	0.3318	0.3316	33.1600
57	160:09:2	0.3319	0.3317	33.1700
58	164:09:2	0.3319	0.3317	33.1700
59	168:09:2	0.3320	0.3318	33.1800
60	172:09:2	0.3322	0.3320	33.2000
61	176:09:2	0.3323	0.3321	33.2100
62	180:09:2	0.3325	0.3323	33.2300
63	184:09:2	0.3326	0.3324	33.2400
64	188:09:2	0.3327	0.3325	33.2500
65	192:09:2	0.3327	0.3325	33.2500
66	196:09:2	0.3328	0.3326	33.2600
67	200:09:2	0.3328	0.3326	33.2600
68	204:09:2	0.3329	0.3327	33.2700
69	208:09:2	0.3330	0.3328	33.2800
70	212:09:2	0.3330	0.3328	33.2800
71	216:09:2	0.3331	0.3329	33.2900
72	220:09:2	0.3331	0.3329	33.2900
73	224:09:2	0.3332	0.3330	33.3000

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

74	228:09:2	0.3333	0.3331	33.3100
75	232:09:2	0.3334	0.3332	33.3200
76	236:09:2	0.3334	0.3332	33.3200
77	240:09:2	0.3334	0.3332	33.3200
78	244:09:2	0.3335	0.3333	33.3300
79	248:09:2	0.3336	0.3334	33.3400
80	252:09:2	0.3336	0.3334	33.3400
81	256:09:2	0.3337	0.3335	33.3500
82	260:09:2	0.3337	0.3335	33.3500
83	264:09:2	0.3338	0.3336	33.3600
84	268:09:2	0.3339	0.3337	33.3700
85	272:09:2	0.3339	0.3337	33.3700
86	276:09:2	0.3339	0.3337	33.3700
87	280:09:2	0.3339	0.3337	33.3700
88	284:09:2	0.3340	0.3338	33.3800
89	288:09:2	0.3341	0.3339	33.3900
90	292:09:2	0.3342	0.3340	33.4000
91	296:09:2	0.3343	0.3341	33.4100
92	300:09:2	0.3344	0.3342	33.4200
93	304:09:2	0.3345	0.3343	33.4300
94	308:09:2	0.3345	0.3343	33.4300
95	312:09:2	0.3345	0.3343	33.4300
96	316:09:2	0.3347	0.3345	33.4500
97	320:09:2	0.3348	0.3346	33.4600
98	324:09:2	0.3350	0.3348	33.4800
99	328:09:2	0.3351	0.3349	33.4900
100	332:09:2	0.3351	0.3349	33.4900
101	336:09:2	0.3352	0.3350	33.5000
102	340:09:2	0.3353	0.3351	33.5100
103	344:09:2	0.3355	0.3353	33.5300
104	348:09:2	0.3358	0.3356	33.5600
105	352:09:2	0.3359	0.3357	33.5700
106	356:09:0	0.3360	0.3358	33.5800
107	360:09:1	0.3361	0.3359	33.5900
108	364:09:2	0.3363	0.3361	33.6100
109	368:09:2	0.3365	0.3363	33.6300
110	372:09:2	0.3367	0.3365	33.6500
111	376:09:2	0.3368	0.3366	33.6600

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

112	380:09:2	0.3368	0.3366	33.6600
113	384:09:2	0.3369	0.3367	33.6700
114	388:09:2	0.3370	0.3368	33.6800
115	392:09:2	0.3371	0.3369	33.6900
116	396:09:2	0.3372	0.3370	33.7000
117	400:09:2	0.3373	0.3371	33.7100
118	404:09:2	0.3373	0.3371	33.7100
119	408:09:2	0.3374	0.3372	33.7200
120	412:09:2	0.3375	0.3373	33.7300
121	416:09:2	0.3375	0.3373	33.7300
122	420:09:2	0.3377	0.3375	33.7500
123	424:09:2	0.3377	0.3375	33.7500
124	428:09:2	0.3378	0.3376	33.7600
125	432:09:2	0.3378	0.3376	33.7600
126	436:09:2	0.3379	0.3377	33.7700
127	440:09:2	0.3381	0.3379	33.7900
128	444:09:2	0.3382	0.3380	33.8000
129	448:09:2	0.3383	0.3381	33.8100
130	452:09:2	0.3383	0.3381	33.8100
131	456:09:2	0.3383	0.3381	33.8100
132	460:09:2	0.3384	0.3382	33.8200
133	464:09:2	0.3385	0.3383	33.8300
134	468:09:2	0.3386	0.3384	33.8400
135	472:09:2	0.3387	0.3385	33.8500
136	476:09:2	0.3387	0.3385	33.8500
137	480:09:2	0.3388	0.3386	33.8600
138	484:09:2	0.3389	0.3387	33.8700
139	488:09:2	0.3391	0.3389	33.8900
140	492:09:2	0.3392	0.3390	33.9000
141	496:09:2	0.3392	0.3390	33.9000
142	500:09:2	0.3393	0.3391	33.9100
143	504:09:2	0.3393	0.3391	33.9100
144	508:09:2	0.3394	0.3392	33.9200
145	512:09:2	0.3395	0.3393	33.9300
146	516:09:2	0.3397	0.3395	33.9500
147	520:09:2	0.3398	0.3396	33.9600
148	524:09:2	0.3399	0.3397	33.9700
149	528:09:2	0.3399	0.3397	33.9700

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

150	532:09:2	0.3400	0.3398	33.9800
151	536:09:2	0.3402	0.3400	34.0000
152	540:09:2	0.3403	0.3401	34.0100
153	544:09:2	0.3404	0.3402	34.0200
154	548:09:2	0.3405	0.3403	34.0300
155	552:09:2	0.3406	0.3404	34.0400
156	556:09:2	0.3407	0.3405	34.0500
157	560:09:2	0.3408	0.3406	34.0600
158	564:09:2	0.3410	0.3408	34.0800
159	568:09:2	0.3410	0.3408	34.0800
160	572:09:2	0.3411	0.3409	34.0900
161	576:09:2	0.3411	0.3409	34.0900
162	580:09:2	0.3412	0.3410	34.1000
163	584:09:2	0.3414	0.3412	34.1200
164	588:09:2	0.3415	0.3413	34.1300
165	592:09:2	0.3416	0.3414	34.1400
166	596:09:2	0.3416	0.3414	34.1400
167	600:09:02	0.3417	0.3415	34.1500
168	604:09:02	0.3418	0.3416	34.1600
169	608:09:02	0.3421	0.3419	34.1900
170	612:09:02	0.3423	0.3421	34.2100
171	616:09:02	0.3424	0.3422	34.2200
172	620:09:02	0.3424	0.3422	34.2200
173	624:09:02	0.3425	0.3423	34.2300
174	628:09:02	0.3427	0.3425	34.2500
175	632:09:02	0.3429	0.3427	34.2700
176	636:09:02	0.3430	0.3428	34.2800
177	640:09:02	0.3431	0.3429	34.2900
178	644:09:02	0.3431	0.3429	34.2900
179	648:09:02	0.3431	0.3429	34.2900
180	652:09:02	0.3432	0.3430	34.3000
181	656:09:02	0.3434	0.3432	34.3200
182	660:09:02	0.3435	0.3433	34.3300
183	664:09:02	0.3436	0.3434	34.3400
184	668:09:02	0.3437	0.3435	34.3500
185	672:09:02	0.3437	0.3435	34.3500
186	676:09:02	0.3438	0.3436	34.3600
187	680:09:02	0.3439	0.3437	34.3700

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

188	684:09:02	0.3441	0.3439	34.3900
189	688:09:02	0.3442	0.3440	34.4000
190	692:09:02	0.3443	0.3441	34.4100
191	696:09:02	0.3443	0.3441	34.4100
192	700:09:02	0.3445	0.3443	34.4300
193	704:09:02	0.3446	0.3444	34.4400
194	708:09:02	0.3448	0.3446	34.4600
195	712:09:02	0.3448	0.3446	34.4600
196	716:09:02	0.3448	0.3446	34.4600
197	720:09:02	0.3449	0.3447	34.4700
198	724:09:02	0.3450	0.3448	34.4800
199	728:09:02	0.3452	0.3450	34.5000
200	732:09:02	0.3453	0.3451	34.5100
201	736:09:02	0.3454	0.3452	34.5200
202	740:09:02	0.3454	0.3452	34.5200
203	744:09:02	0.3455	0.3453	34.5300
204	748:09:02	0.3455	0.3453	34.5300
205	752:09:02	0.3456	0.3454	34.5400
206	756:09:02	0.3456	0.3454	34.5400
207	760:09:02	0.3457	0.3455	34.5500
208	764:09:02	0.3457	0.3455	34.5500
209	768:09:02	0.3458	0.3456	34.5600
210	772:09:02	0.3458	0.3456	34.5600
211	776:09:02	0.3460	0.3458	34.5800
212	780:09:02	0.3461	0.3459	34.5900
213	784:09:02	0.3461	0.3459	34.5900
214	788:09:02	0.3461	0.3459	34.5900
215	792:09:02	0.3462	0.3460	34.6000
216	796:09:02	0.3462	0.3460	34.6000
217	800:09:02	0.3463	0.3461	34.6100
218	804:09:02	0.3464	0.3462	34.6200
219	808:09:02	0.3464	0.3462	34.6200
220	812:09:02	0.3465	0.3463	34.6300
221	816:09:02	0.3465	0.3463	34.6300
222	820:09:02	0.3466	0.3464	34.6400
223	824:09:02	0.3467	0.3465	34.6500
224	828:09:02	0.3468	0.3466	34.6600
225	832:09:02	0.3469	0.3467	34.6700

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

226	836:09:02	0.3469	0.3467	34.6700
227	840:09:02	0.3470	0.3468	34.6800
228	844:09:02	0.3470	0.3468	34.6800
229	848:09:02	0.3471	0.3469	34.6900
230	852:09:02	0.3473	0.3471	34.7100
231	856:09:02	0.3473	0.3471	34.7100
232	860:09:02	0.3474	0.3472	34.7200
233	864:09:02	0.3474	0.3472	34.7200
234	868:09:02	0.3475	0.3473	34.7300
235	872:09:02	0.3476	0.3474	34.7400
236	876:09:02	0.3478	0.3476	34.7600
237	880:09:02	0.3478	0.3476	34.7600
238	884:09:02	0.3479	0.3477	34.7700
239	888:09:02	0.3479	0.3477	34.7700
240	892:09:02	0.3480	0.3478	34.7800
241	896:09:02	0.3480	0.3478	34.7800
242	900:09:02	0.3482	0.3480	34.8000
243	904:09:02	0.3482	0.3480	34.8000
244	908:09:02	0.3483	0.3481	34.8100
245	912:09:02	0.3483	0.3481	34.8100
246	916:09:02	0.3484	0.3482	34.8200
247	920:09:02	0.3485	0.3483	34.8300
248	924:09:02	0.3486	0.3484	34.8400
249	928:09:02	0.3487	0.3485	34.8500
250	932:09:02	0.3487	0.3485	34.8500
251	936:09:02	0.3487	0.3485	34.8500
252	940:09:02	0.3488	0.3486	34.8600
253	944:09:02	0.3490	0.3488	34.8800
254	948:09:02	0.3491	0.3489	34.8900
255	952:09:02	0.3492	0.3490	34.9000
256	956:09:02	0.3492	0.3490	34.9000
257	960:09:02	0.3493	0.3491	34.9100
258	964:09:02	0.3494	0.3492	34.9200
259	968:09:02	0.3495	0.3493	34.9300
260	972:09:02	0.3496	0.3494	34.9400
261	976:09:02	0.3496	0.3494	34.9400
262	980:09:02	0.3497	0.3495	34.9500
263	984:09:02	0.3497	0.3495	34.9500

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

264	988:09:02	0.3498	0.3496	34.9600
265	992:09:02	0.3499	0.3497	34.9700
266	996:09:02	0.3499	0.3497	34.9700
267	1000:09:02	0.3499	0.3497	34.9700
268	1004:09:02	0.3500	0.3498	34.9800
269	1008:09:02	0.3500	0.3498	34.9800
270	1012:09:02	0.3501	0.3499	34.9900
271	1016:09:02	0.3502	0.3500	35.0000
272	1020:09:02	0.3502	0.3500	35.0000
273	1024:09:02	0.3502	0.3500	35.0000
274	1028:09:02	0.3503	0.3501	35.0100
275	1032:09:02	0.3503	0.3501	35.0100
276	1036:09:02	0.3503	0.3501	35.0100
277	1040:09:02	0.3504	0.3502	35.0200
278	1044:09:02	0.3505	0.3503	35.0300
279	1048:09:02	0.3505	0.3503	35.0300
280	1052:09:02	0.3506	0.3504	35.0400
281	1056:09:02	0.3506	0.3504	35.0400
282	1060:09:02	0.3506	0.3504	35.0400
283	1064:09:02	0.3507	0.3505	35.0500
284	1068:09:02	0.3508	0.3506	35.0600
285	1072:09:02	0.3509	0.3507	35.0700
286	1076:09:02	0.3509	0.3507	35.0700
287	1080:09:02	0.3509	0.3507	35.0700
288	1084:09:02	0.3510	0.3508	35.0800
289	1088:09:02	0.3510	0.3508	35.0800
290	1092:09:02	0.3511	0.3509	35.0900
291	1096:09:02	0.3511	0.3509	35.0900
292	1100:09:02	0.3511	0.3509	35.0900
293	1104:09:02	0.3511	0.3509	35.0900
294	1108:09:02	0.3512	0.3510	35.1000
295	1112:09:02	0.3512	0.3510	35.1000
296	1116:09:02	0.3513	0.3511	35.1100
297	1120:09:02	0.3513	0.3511	35.1100
298	1124:09:02	0.3513	0.3511	35.1100
299	1128:09:02	0.3514	0.3512	35.1200
300	1132:09:02	0.3514	0.3512	35.1200
301	1136:09:02	0.3515	0.3513	35.1300

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

302	1140:09:02	0.3516	0.3514	35.1400
303	1144:09:02	0.3516	0.3514	35.1400
304	1148:09:02	0.3516	0.3514	35.1400
305	1152:09:02	0.3516	0.3514	35.1400
306	1156:09:02	0.3517	0.3515	35.1500
307	1160:09:02	0.3519	0.3517	35.1700
308	1164:09:02	0.3520	0.3518	35.1800
309	1168:09:02	0.3520	0.3518	35.1800
310	1172:09:02	0.3520	0.3518	35.1800
311	1176:09:02	0.3520	0.3518	35.1800
312	1180:09:02	0.3521	0.3519	35.1900
313	1184:09:02	0.3522	0.3520	35.2000
314	1188:09:02	0.3523	0.3521	35.2100
315	1192:09:02	0.3524	0.3522	35.2200
316	1196:09:02	0.3525	0.3523	35.2300
317	1200:09:02	0.3526	0.3524	35.2400
318	1204:09:02	0.3527	0.3525	35.2500
319	1208:09:02	0.3528	0.3526	35.2600
320	1212:09:02	0.3530	0.3528	35.2800
321	1216:09:02	0.3531	0.3529	35.2900
322	1220:09:02	0.3532	0.3530	35.3000
323	1224:09:02	0.3533	0.3531	35.3100
324	1228:09:02	0.3534	0.3532	35.3200
325	1232:09:02	0.3535	0.3533	35.3300
326	1236:09:02	0.3536	0.3534	35.3400
327	1240:09:02	0.3537	0.3535	35.3500
328	1244:09:02	0.3538	0.3536	35.3600
329	1248:09:02	0.3509	0.3537	35.3700
330	1252:09:02	0.3509	0.3538	35.3800
331	1256:09:02	0.3510	0.3539	35.3900
332	1260:09:02	0.3511	0.3540	35.4000
333	1264:09:02	0.3512	0.3541	35.4100
334	1268:09:02	0.3513	0.3541	35.4100
335	1272:09:02	0.3514	0.3542	35.4200
336	1276:09:02	0.3515	0.3543	35.4300
337	1280:09:02	0.3516	0.3544	35.4400
338	1284:09:02	0.3516	0.3545	35.4500
339	1288:09:02	0.3517	0.3546	35.4600

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

340	1292:09:02	0.3518	0.3547	35.4700
341	1296:09:02	0.3519	0.3548	35.4800
342	1300:09:02	0.3520	0.3549	35.4900
343	1304:09:02	0.3521	0.3549	35.4900
344	1308:09:02	0.3522	0.3550	35.5000
345	1312:09:02	0.3523	0.3551	35.5100
346	1316:09:02	0.3524	0.3552	35.5200
347	1320:09:02	0.3524	0.3553	35.5300
348	1324:09:02	0.3525	0.3554	35.5400
349	1328:09:02	0.3526	0.3555	35.5500
350	1332:09:02	0.3527	0.3556	35.5600
351	1336:09:02	0.3528	0.3556	35.5600
352	1340:09:02	0.3529	0.3557	35.5700
353	1344:09:02	0.3530	0.3558	35.5800
354	1348:09:02	0.3531	0.3559	35.5900
355	1352:09:02	0.3532	0.3560	35.6000
356	1356:09:02	0.3532	0.3561	35.6100
357	1360:09:02	0.3533	0.3562	35.6200
358	1364:09:02	0.3534	0.3563	35.6300
359	1368:09:02	0.3535	0.3564	35.6400
360	1372:09:02	0.3536	0.3564	35.6400
361	1376:09:02	0.3537	0.3565	35.6500
362	1380:09:02	0.3538	0.3566	35.6600
363	1384:09:02	0.3539	0.3567	35.6700
364	1388:09:02	0.3540	0.3568	35.6800
365	1392:09:02	0.3540	0.3569	35.6900
366	1396:09:02	0.3541	0.3570	35.7000
367	1400:09:02	0.3542	0.3571	35.7100
368	1404:09:02	0.3543	0.3572	35.7200
369	1408:09:02	0.3544	0.3573	35.7300
370	1412:09:02	0.3545	0.3575	35.7500
371	1416:09:02	0.3546	0.3576	35.7600
372	1420:09:02	0.3547	0.3577	35.7700
373	1424:09:02	0.3549	0.3578	35.7800
374	1428:09:02	0.3550	0.3579	35.7900
375	1432:09:02	0.3551	0.3580	35.8000
376	1436:09:02	0.3552	0.3581	35.8100
377	1440:09:02	0.3553	0.3583	35.8300

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

378	1444:09:02	0.3554	0.3584	35.8400
379	1448:09:02	0.3555	0.3585	35.8500
380	1452:09:02	0.3557	0.3586	35.8600
381	1456:09:02	0.3558	0.3587	35.8700
382	1460:09:02	0.3559	0.3588	35.8800
383	1464:09:02	0.3560	0.3589	35.8900
384	1468:09:02	0.3561	0.3591	35.9100
385	1472:09:02	0.3562	0.3592	35.9200
386	1476:09:02	0.3563	0.3593	35.9300
387	1480:09:02	0.3565	0.3594	35.9400
388	1484:09:02	0.3566	0.3595	35.9500
389	1488:09:02	0.3567	0.3596	35.9600
390	1492:09:02	0.3568	0.3597	35.9700
391	1496:09:02	0.3569	0.3598	35.9800
392	1500:09:02	0.3570	0.3600	36.0000
393	1504:09:02	0.3571	0.3601	36.0100
394	1508:09:02	0.3573	0.3602	36.0200
395	1512:09:02	0.3574	0.3603	36.0300
396	1516:09:02	0.3575	0.3604	36.0400
397	1520:09:02	0.3576	0.3605	36.0500
398	1524:09:02	0.3577	0.3606	36.0600
399	1528:09:02	0.3578	0.3608	36.0800
400	1532:09:02	0.3579	0.3609	36.0900
401	1536:09:02	0.3581	0.3610	36.1000
402	1540:09:02	0.3582	0.3611	36.1100
403	1544:09:02	0.3584	0.3613	36.1300
404	1548:09:02	0.3585	0.3614	36.1400
405	1552:09:02	0.3587	0.3616	36.1600
406	1556:09:02	0.3588	0.3618	36.1800
407	1560:09:02	0.3590	0.3619	36.1900
408	1564:09:02	0.3591	0.3621	36.2100
409	1568:09:02	0.3593	0.3622	36.2200
410	1572:09:02	0.3594	0.3624	36.2400
411	1576:09:02	0.3596	0.3625	36.2500
412	1580:09:02	0.3597	0.3627	36.2700
413	1584:09:02	0.3599	0.3628	36.2800
414	1588:09:02	0.3600	0.3630	36.3000
415	1592:09:02	0.3602	0.3631	36.3100

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

416	1596:09:02	0.3603	0.3633	36.3300
417	1600:09:02	0.3605	0.3634	36.3400
418	1604:09:02	0.3606	0.3636	36.3600
419	1608:09:02	0.3608	0.3637	36.3700
420	1612:09:02	0.3609	0.3639	36.3900
421	1616:09:02	0.3611	0.3640	36.4000
422	1620:09:02	0.3613	0.3642	36.4200
423	1624:09:02	0.3614	0.3643	36.4300
424	1628:09:02	0.3616	0.3645	36.4500
425	1632:09:02	0.3617	0.3646	36.4600
426	1636:09:02	0.3619	0.3648	36.4800
427	1640:09:02	0.3620	0.3650	36.5000
428	1644:09:02	0.3622	0.3651	36.5100
429	1648:09:02	0.3623	0.3653	36.5300
430	1652:09:02	0.3625	0.3654	36.5400
431	1656:09:02	0.3626	0.3656	36.5600
432	1660:09:02	0.3628	0.3657	36.5700
433	1664:09:02	0.3629	0.3659	36.5900
434	1668:09:02	0.3631	0.3660	36.6000
435	1672:09:02	0.3632	0.3662	36.6200
436	1676:09:02	0.3634	0.3663	36.6300
437	1680:09:02	0.3635	0.3665	36.6500
438	1684:09:02	0.3637	0.3666	36.6600
439	1688:09:02	0.3638	0.3668	36.6800
440	1692:09:02	0.3640	0.3669	36.6900
441	1696:09:02	0.3641	0.3671	36.7100
442	1700:09:02	0.3643	0.3672	36.7200
443	1704:09:02	0.3645	0.3674	36.7400
444	1708:09:02	0.3646	0.3676	36.7600
445	1712:09:02	0.3648	0.3678	36.7800
446	1716:09:02	0.3650	0.3679	36.7900
447	1720:09:02	0.3652	0.3681	36.8100
448	1724:09:02	0.3654	0.3683	36.8300
449	1728:09:02	0.3655	0.3685	36.8500
450	1732:09:02	0.3657	0.3687	36.8700
451	1736:09:02	0.3659	0.3688	36.8800
452	1740:09:02	0.3661	0.3690	36.9000
453	1744:09:02	0.3663	0.3692	36.9200

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

454	1748:09:02	0.3664	0.3694	36.9400
455	1752:09:02	0.3666	0.3696	36.9600
456	1756:09:02	0.3668	0.3697	36.9700
457	1760:09:02	0.3670	0.3699	36.9900
458	1764:09:02	0.3672	0.3701	37.0100
459	1768:09:02	0.3674	0.3703	37.0300
460	1772:09:02	0.3675	0.3705	37.0500
461	1776:09:02	0.3677	0.3707	37.0700
462	1780:09:02	0.3679	0.3708	37.0800
463	1784:09:02	0.3681	0.3710	37.1000
464	1788:09:02	0.3683	0.3712	37.1200
465	1792:09:02	0.3684	0.3714	37.1400
466	1796:09:02	0.3686	0.3716	37.1600
467	1800:09:02	0.3688	0.3717	37.1700
468	1804:09:02	0.3690	0.3719	37.1900
469	1808:09:02	0.3692	0.3721	37.2100
470	1812:09:02	0.3693	0.3723	37.2300
471	1816:09:02	0.3695	0.3725	37.2500
472	1820:09:02	0.3697	0.3726	37.2600
473	1824:09:02	0.3699	0.3728	37.2800
474	1828:09:02	0.3701	0.3730	37.3000
475	1832:09:02	0.3703	0.3732	37.3200
476	1836:09:02	0.3704	0.3734	37.3400
477	1840:09:02	0.3706	0.3736	37.3600
478	1844:09:02	0.3708	0.3737	37.3700
479	1848:09:02	0.3710	0.3739	37.3900
480	1852:09:02	0.3712	0.3741	37.4100
481	1856:09:02	0.3713	0.3743	37.4300
482	1860:09:02	0.3715	0.3745	37.4500
483	1864:09:02	0.3717	0.3746	37.4600
484	1868:09:02	0.3719	0.3748	37.4800
485	1872:09:02	0.3721	0.3750	37.5000
486	1876:09:02	0.3723	0.3752	37.5200
487	1880:09:02	0.3724	0.3754	37.5400
488	1884:09:02	0.3726	0.3755	37.5500
489	1888:09:02	0.3728	0.3757	37.5700
490	1892:09:02	0.3730	0.3759	37.5900
491	1896:09:02	0.3731	0.3761	37.6100

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

492	1900:09:02	0.3733	0.3763	37.6300
493	1904:09:02	0.3735	0.3764	37.6400
494	1908:09:02	0.3737	0.3766	37.6600
495	1912:09:02	0.3739	0.3768	37.6800
496	1916:09:02	0.3740	0.3770	37.7000
497	1920:09:02	0.3742	0.3771	37.7100
498	1924:09:02	0.3744	0.3773	37.7300
499	1928:09:02	0.3746	0.3775	37.7500
500	1932:09:02	0.3747	0.3777	37.7700
501	1936:09:02	0.3749	0.3779	37.7900
502	1940:09:02	0.3751	0.3780	37.8000
503	1944:09:02	0.3753	0.3782	37.8200
504	1948:09:02	0.3755	0.3784	37.8400
505	1952:09:02	0.3756	0.3786	37.8600
506	1956:09:02	0.3758	0.3787	37.8700
507	1960:09:02	0.3760	0.3789	37.8900
508	1964:09:02	0.3762	0.3791	37.9100
509	1968:09:02	0.3763	0.3793	37.9300
510	1972:09:02	0.3765	0.3795	37.9500
511	1976:09:02	0.3767	0.3796	37.9600
512	1980:09:02	0.3769	0.3798	37.9800
513	1984:09:02	0.3771	0.3800	38.0000
514	1988:09:02	0.3772	0.3802	38.0200
515	1992:09:02	0.3774	0.3804	38.0400
516	1996:09:02	0.3776	0.3805	38.0500
517	2000:09:02	0.3778	0.3807	38.0700
518	2004:09:02	0.3779	0.3809	38.0900
519	2008:09:02	0.3781	0.3811	38.1100
520	2012:09:02	0.3783	0.3812	38.1200
521	2016:09:02	0.3785	0.3814	38.1400
522	2020:09:02	0.3787	0.3816	38.1600
523	2024:09:02	0.3788	0.3818	38.1800
524	2028:09:02	0.3790	0.3820	38.2000
525	2032:09:02	0.3792	0.3821	38.2100
526	2036:09:02	0.3794	0.3823	38.2300
527	2040:09:02	0.3796	0.3825	38.2500
528	2044:09:02	0.3797	0.3826	38.2600
529	2048:09:02	0.3798	0.3828	38.2800

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

530	2052:09:02	0.3800	0.3829	38.2900
531	2056:09:02	0.3801	0.3831	38.3100
532	2060:09:03	0.3803	0.3832	38.3200
533	2064:09:02	0.3804	0.3833	38.3300
534	2068:09:02	0.3806	0.3835	38.3500
535	2072:09:02	0.3807	0.3836	38.3600
536	2076:09:02	0.3808	0.3838	38.3800
537	2080:09:02	0.3810	0.3839	38.3900
538	2084:09:02	0.3811	0.3841	38.4100
539	2088:09:02	0.3813	0.3842	38.4200
540	2092:09:02	0.3814	0.3843	38.4300
541	2096:09:02	0.3816	0.3845	38.4500
542	2100:09:02	0.3817	0.3846	38.4600
543	2104:09:02	0.3818	0.3848	38.4800
544	2108:09:02	0.3820	0.3849	38.4900
545	2112:09:02	0.3821	0.3851	38.5100
546	2116:09:02	0.3823	0.3852	38.5200
547	2120:09:02	0.3824	0.3853	38.5300
548	2124:09:02	0.3826	0.3855	38.5500
549	2128:09:02	0.3827	0.3856	38.5600
550	2132:09:02	0.3828	0.3858	38.5800
551	2136:09:02	0.3830	0.3859	38.5900
552	2140:09:02	0.3831	0.3861	38.6100
553	2144:09:03	0.3833	0.3862	38.6200
554	2148:09:03	0.3834	0.3863	38.6300
555	2152:09:02	0.3836	0.3865	38.6500
556	2156:09:03	0.3837	0.3866	38.6600
557	2160:09:03	0.3838	0.3868	38.6800
558	2164:09:02	0.3840	0.3869	38.6900
559	2168:09:03	0.3841	0.3871	38.7100
560	2172:09:03	0.3843	0.3872	38.7200
561	2176:09:02	0.3844	0.3873	38.7300
562	2180:09:03	0.3846	0.3875	38.7500
563	2184:09:03	0.3847	0.3876	38.7600
564	2188:09:02	0.3848	0.3878	38.7800
565	2192:09:03	0.3850	0.3879	38.7900
566	2196:09:03	0.3851	0.3881	38.8100
567	2200:09:02	0.3853	0.3882	38.8200

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

568	2204:09:03	0.3854	0.3883	38.8300
569	2208:09:03	0.3856	0.3885	38.8500
570	2212:09:02	0.3856	0.3886	38.8600
571	2216:09:03	0.3857	0.3887	38.8700
572	2220:09:03	0.3858	0.3888	38.8800
573	2224:09:02	0.3859	0.3888	38.8800
574	2228:09:03	0.3860	0.3889	38.8900
575	2232:09:03	0.3861	0.3890	38.9000
576	2236:09:02	0.3862	0.3891	38.9100
577	2240:09:03	0.3863	0.3892	38.9200
578	2244:09:03	0.3863	0.3893	38.9300
579	2248:09:02	0.3864	0.3894	38.9400
580	2252:09:03	0.3865	0.3895	38.9500
581	2256:09:03	0.3866	0.3895	38.9500
582	2260:09:02	0.3867	0.3896	38.9600
583	2264:09:03	0.3868	0.3897	38.9700
584	2268:09:03	0.3869	0.3898	38.9800
585	2272:09:02	0.3870	0.3899	38.9900
586	2276:09:03	0.3870	0.3900	39.0000
587	2280:09:03	0.3871	0.3901	39.0100
588	2284:09:02	0.3872	0.3902	39.0200
589	2288:09:03	0.3873	0.3903	39.0300
590	2292:09:03	0.3874	0.3903	39.0300
591	2296:09:02	0.3875	0.3904	39.0400
592	2300:09:03	0.3876	0.3905	39.0500
593	2304:09:03	0.3877	0.3906	39.0600
594	2308:09:02	0.3878	0.3907	39.0700
595	2312:09:03	0.3878	0.3908	39.0800
596	2316:09:03	0.3879	0.3909	39.0900
597	2320:09:02	0.3880	0.3910	39.1000
598	2324:09:03	0.3881	0.3910	39.1000
599	2328:09:03	0.3882	0.3911	39.1100
600	2332:09:02	0.3883	0.3912	39.1200
601	2336:09:03	0.3884	0.3913	39.1300
602	2340:09:03	0.3885	0.3914	39.1400
603	2344:09:02	0.3885	0.3915	39.1500
604	2348:09:03	0.3886	0.3916	39.1600
605	2352:09:03	0.3887	0.3917	39.1700

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

606	2356:09:02	0.3888	0.3917	39.1700
607	2360:09:03	0.3889	0.3918	39.1800
608	2364:09:03	0.3890	0.3919	39.1900
609	2368:09:02	0.3891	0.3920	39.2000
610	2372:09:03	0.3892	0.3921	39.2100
611	2376:09:02	0.3893	0.3922	39.2200
612	2380:09:02	0.3893	0.3923	39.2300
613	2384:09:03	0.3894	0.3924	39.2400
614	2388:09:02	0.3895	0.3925	39.2500
615	2392:09:02	0.3896	0.3925	39.2500
616	2396:09:03	0.3897	0.3926	39.2600
617	2400:09:02	0.3898	0.3927	39.2700
618	2404:09:02	0.3899	0.3928	39.2800
619	2408:09:03	0.3900	0.3929	39.2900
620	2412:09:02	0.3900	0.3930	39.3000
621	2416:09:02	0.3901	0.3931	39.3100
622	2420:09:03	0.3902	0.3932	39.3200
623	2424:09:02	0.3903	0.3932	39.3200
624	2428:09:02	0.3904	0.3933	39.3300
625	2432:09:03	0.3905	0.3934	39.3400
626	2436:09:02	0.3906	0.3935	39.3500
627	2440:09:02	0.3907	0.3936	39.3600
628	2444:09:03	0.3907	0.3937	39.3700
629	2448:09:02	0.3908	0.3938	39.3800
630	2452:09:02	0.3909	0.3939	39.3900
631	2456:09:03	0.3910	0.3940	39.4000
632	2460:09:02	0.3911	0.3940	39.4000
633	2464:09:02	0.3912	0.3941	39.4100
634	2468:09:03	0.3913	0.3942	39.4200
635	2472:09:02	0.3914	0.3943	39.4300
636	2476:09:02	0.3915	0.3944	39.4400
637	2480:09:03	0.3915	0.3945	39.4500
638	2484:09:02	0.3916	0.3946	39.4600
639	2488:09:02	0.3917	0.3947	39.4700
640	2492:09:03	0.3918	0.3947	39.4700
641	2496:09:02	0.3919	0.3948	39.4800
642	2500:09:02	0.3920	0.3949	39.4900
643	2504:09:03	0.3921	0.3950	39.5000

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

644	2508:09:02	0.3922	0.3951	39.5100
645	2512:09:02	0.3922	0.3952	39.5200
646	2516:09:03	0.3923	0.3953	39.5300
647	2520:09:02	0.3924	0.3954	39.5400
648	2524:09:02	0.3925	0.3954	39.5400
649	2528:09:03	0.3926	0.3955	39.5500
650	2532:09:02	0.3927	0.3956	39.5600
651	2536:09:02	0.3928	0.3957	39.5700
652	2540:09:03	0.3929	0.3958	39.5800
653	2544:09:02	0.3930	0.3959	39.5900
654	2548:09:02	0.3930	0.3960	39.6000
655	2552:09:03	0.3931	0.3961	39.6100
656	2556:09:02	0.3932	0.3962	39.6200
657	2560:09:02	0.3933	0.3963	39.6300
658	2564:09:03	0.3934	0.3964	39.6400
659	2568:09:02	0.3935	0.3965	39.6500
660	2572:09:02	0.3936	0.3966	39.6600
661	2576:09:03	0.3937	0.3966	39.6600
662	2580:09:02	0.3938	0.3967	39.6700
663	2584:09:02	0.3939	0.3968	39.6800
664	2588:09:03	0.3940	0.3969	39.6900
665	2592:09:02	0.3942	0.3971	39.7100
666	2596:09:02	0.3943	0.3972	39.7200
667	2600:09:03	0.3944	0.3973	39.7300
668	2604:09:02	0.3945	0.3974	39.7400
669	2608:09:02	0.3946	0.3975	39.7500
670	2612:09:03	0.3947	0.3976	39.7600
671	2616:09:02	0.3948	0.3977	39.7700
672	2620:09:02	0.3949	0.3978	39.7800
673	2624:09:03	0.3950	0.3979	39.7900
674	2628:09:02	0.3952	0.3981	39.8100
675	2632:09:02	0.3953	0.3982	39.8200
676	2636:09:03	0.3954	0.3983	39.8300
677	2640:09:02	0.3955	0.3984	39.8400
678	2644:09:02	0.3956	0.3985	39.8500
679	2648:09:03	0.3957	0.3986	39.8600
680	2652:09:02	0.3958	0.3987	39.8700
681	2656:09:02	0.3959	0.3988	39.8800

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

682	2660:09:03	0.3960	0.3990	39.9000
683	2664:09:02	0.3961	0.3991	39.9100
684	2668:09:02	0.3962	0.3992	39.9200
685	2672:09:03	0.3963	0.3993	39.9300
686	2676:09:02	0.3964	0.3994	39.9400
687	2680:09:02	0.3965	0.3995	39.9500
688	2684:09:03	0.3966	0.3996	39.9600
689	2688:09:02	0.3967	0.3997	39.9700
690	2692:09:02	0.3968	0.3998	39.9800
691	2696:09:03	0.3969	0.3999	39.9900
692	2700:09:02	0.3971	0.4000	40.0000
693	2704:09:02	0.3973	0.4002	40.0200
694	2708:09:03	0.3974	0.4003	40.0300
695	2712:09:02	0.3975	0.4004	40.0400
696	2716:09:02	0.3977	0.4006	40.0600
697	2720:09:03	0.3978	0.4007	40.0700
698	2724:09:02	0.3979	0.4008	40.0800
699	2728:09:02	0.3980	0.4009	40.0900
700	2732:09:03	0.3981	0.4011	40.1100
701	2736:09:02	0.3982	0.4012	40.1200
702	2740:09:02	0.3984	0.4013	40.1300
703	2744:09:02	0.3985	0.4014	40.1400
704	2748:09:02	0.3986	0.4015	40.1500
705	2752:09:02	0.3987	0.4016	40.1600
706	2756:09:02	0.3988	0.4017	40.1700
707	2760:09:02	0.3989	0.4018	40.1800
708	2764:09:02	0.3991	0.4020	40.2000
709	2768:09:02	0.3992	0.4022	40.2200
710	2772:09:02	0.3993	0.4023	40.2300
711	2776:09:02	0.3995	0.4024	40.2400
712	2780:09:02	0.3997	0.4026	40.2600
713	2784:09:02	0.3998	0.4027	40.2700
714	2788:09:02	0.3999	0.4028	40.2800
715	2792:09:02	0.4000	0.4029	40.2900
716	2796:09:02	0.4001	0.4031	40.3100
717	2800:09:02	0.4003	0.4033	40.3300
718	2804:09:02	0.4005	0.4035	40.3500
719	2808:09:02	0.4007	0.4037	40.3700

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

720	2812:09:02	0.4009	0.4038	40.3800
721	2816:09:02	0.4010	0.4039	40.3900
722	2820:09:02	0.4011	0.4040	40.4000
723	2824:09:02	0.4013	0.4042	40.4200
724	2828:09:02	0.4014	0.4043	40.4300
725	2832:09:02	0.4016	0.4045	40.4500
726	2836:09:02	0.4017	0.4046	40.4600
727	2840:09:02	0.4018	0.4048	40.4800
728	2844:09:02	0.4020	0.4049	40.4900
729	2848:09:02	0.4022	0.4051	40.5100
730	2852:09:02	0.4023	0.4052	40.5200
731	2856:09:02	0.4024	0.4053	40.5300
732	2860:09:02	0.4025	0.4054	40.5400
733	2864:09:02	0.4026	0.4056	40.5600
734	2868:09:02	0.4027	0.4057	40.5700
735	2872:09:02	0.4028	0.4058	40.5800
736	2876:09:02	0.4029	0.4059	40.5900
737	2880:09:02	0.4030	0.4060	40.6000
738	2884:09:02	0.4031	0.4061	40.6100
739	2888:09:02	0.4031	0.4061	40.6100
740	2892:09:02	0.4032	0.4062	40.6200
741	2896:09:02	0.4033	0.4063	40.6300
742	2900:09:02	0.4034	0.4063	40.6300
743	2904:09:02	0.4035	0.4064	40.6400
744	2908:09:02	0.4036	0.4065	40.6500
745	2912:09:02	0.4037	0.4066	40.6600
746	2916:09:02	0.4038	0.4067	40.6700
747	2920:09:02	0.4038	0.4068	40.6800
748	2924:09:02	0.4039	0.4068	40.6800
749	2928:09:02	0.4040	0.4069	40.6900
750	2932:09:02	0.4040	0.4070	40.7000
751	2936:09:02	0.4041	0.4070	40.7000
752	2940:09:02	0.4042	0.4071	40.7100
753	2944:09:02	0.4042	0.4072	40.7200
754	2948:09:02	0.4043	0.4072	40.7200
755	2952:09:02	0.4044	0.4073	40.7300
756	2956:09:02	0.4044	0.4074	40.7400
757	2960:09:02	0.4045	0.4074	40.7400

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

758	2964:09:01	0.4046	0.4075	40.7500
759	2968:09:01	0.4046	0.4076	40.7600
760	2972:09:00	0.4047	0.4076	40.7600
761	2976:08:59	0.4047	0.4077	40.7700
762	2980:08:59	0.4048	0.4077	40.7700
763	2984:08:58	0.4049	0.4078	40.7800
764	2988:08:58	0.4049	0.4079	40.7900
765	2992:08:57	0.4050	0.4079	40.7900
766	2996:08:57	0.4051	0.4080	40.8000
767	3000:08:56	0.4051	0.4081	40.8100
768	3004:08:55	0.4052	0.4082	40.8200
769	3008:08:55	0.4053	0.4082	40.8200
770	3012:08:54	0.4054	0.4083	40.8300
771	3016:08:54	0.4054	0.4084	40.8400
772	3020:08:53	0.4055	0.4084	40.8400
773	3024:08:52	0.4056	0.4085	40.8500
774	3028:08:52	0.4056	0.4085	40.8500
775	3032:08:51	0.4056	0.4086	40.8600
776	3036:08:51	0.4057	0.4087	40.8700
777	3040:08:50	0.4058	0.4087	40.8700
778	3044:08:50	0.4059	0.4088	40.8800
779	3048:08:49	0.4059	0.4089	40.8900
780	3052:08:48	0.4060	0.4089	40.8900
781	3056:08:48	0.4061	0.4090	40.9000
782	3060:08:47	0.4061	0.4091	40.9100
783	3064:08:47	0.4062	0.4091	40.9100
784	3068:08:46	0.4063	0.4092	40.9200
785	3072:08:46	0.4063	0.4093	40.9300
786	3076:08:45	0.4064	0.4094	40.9400
787	3080:08:44	0.4065	0.4094	40.9400
788	3084:08:44	0.4066	0.4095	40.9500
789	3088:08:43	0.4066	0.4096	40.9600
790	3092:08:43	0.4067	0.4096	40.9600
791	3096:08:42	0.4068	0.4097	40.9700
792	3100:08:42	0.4068	0.4098	40.9800
793	3104:08:41	0.4069	0.4098	40.9800
794	3108:08:40	0.4070	0.4099	40.9900
795	3112:08:40	0.4070	0.4100	41.0000

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

796	3116:08:39	0.4071	0.4101	41.0100
797	3120:08:39	0.4072	0.4101	41.0100
798	3124:08:38	0.4073	0.4102	41.0200
799	3128:08:38	0.4073	0.4103	41.0300
800	3132:08:37	0.4074	0.4103	41.0300
801	3136:08:36	0.4075	0.4104	41.0400
802	3140:08:36	0.4075	0.4105	41.0500
803	3144:08:35	0.4076	0.4105	41.0500
804	3148:08:35	0.4077	0.4106	41.0600
805	3152:08:34	0.4077	0.4107	41.0700
806	3156:08:33	0.4078	0.4108	41.0800
807	3160:08:33	0.4079	0.4108	41.0800
808	3164:08:32	0.4080	0.4109	41.0900
809	3168:08:32	0.4080	0.4110	41.1000
810	3172:08:31	0.4081	0.4110	41.1000
811	3176:08:31	0.4082	0.4111	41.1100
812	3180:08:30	0.4082	0.4112	41.1200
813	3184:08:29	0.4083	0.4112	41.1200
814	3188:08:29	0.4084	0.4113	41.1300
815	3192:08:28	0.4084	0.4114	41.1400
816	3196:08:28	0.4085	0.4115	41.1500
817	3200:08:27	0.4086	0.4115	41.1500
818	3204:08:27	0.4087	0.4116	41.1600
819	3208:08:26	0.4087	0.4117	41.1700
820	3212:08:25	0.4088	0.4117	41.1700
821	3216:08:25	0.4089	0.4118	41.1800
822	3220:08:24	0.4089	0.4119	41.1900
823	3224:08:24	0.4090	0.4119	41.1900
824	3228:08:23	0.4091	0.4120	41.2000
825	3232:08:23	0.4091	0.4121	41.2100
826	3236:08:22	0.4092	0.4122	41.2200
827	3240:08:21	0.4093	0.4122	41.2200
828	3244:08:21	0.4094	0.4123	41.2300
829	3248:08:20	0.4094	0.4124	41.2400
830	3252:08:20	0.4095	0.4124	41.2400
831	3256:08:19	0.4096	0.4125	41.2500
832	3260:08:19	0.4096	0.4126	41.2600
833	3264:08:18	0.4097	0.4126	41.2600

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

834	3268:08:17	0.4098	0.4127	41.2700
835	3272:08:17	0.4099	0.4128	41.2800
836	3276:08:16	0.4100	0.4129	41.2900
837	3280:08:16	0.4100	0.4130	41.3000
838	3284:08:15	0.4101	0.4130	41.3000
839	3288:08:14	0.4101	0.4131	41.3100
840	3292:08:14	0.4102	0.4131	41.3100
841	3296:08:13	0.4102	0.4132	41.3200
842	3300:08:13	0.4103	0.4132	41.3200
843	3304:08:12	0.4104	0.4133	41.3300
844	3308:08:12	0.4104	0.4134	41.3400
845	3312:08:11	0.4105	0.4135	41.3500
846	3316:08:10	0.4106	0.4135	41.3500
847	3320:08:10	0.4107	0.4136	41.3600
848	3324:08:09	0.4108	0.4137	41.3700
849	3328:08:09	0.4108	0.4138	41.3800
850	3332:08:08	0.4109	0.4139	41.3900
851	3336:08:08	0.4110	0.4140	41.4000
852	3340:08:07	0.4111	0.4141	41.4100
853	3344:08:06	0.4112	0.4142	41.4200
854	3348:08:06	0.4113	0.4143	41.4300
855	3352:08:05	0.4114	0.4144	41.4400
856	3356:08:05	0.4115	0.4144	41.4400
857	3360:08:04	0.4116	0.4145	41.4500
858	3364:08:04	0.4116	0.4146	41.4600
859	3368:08:03	0.4117	0.4146	41.4600
860	3372:08:02	0.4117	0.4147	41.4700
861	3376:08:02	0.4118	0.4147	41.4700
862	3380:08:01	0.4119	0.4148	41.4800
863	3384:08:01	0.4119	0.4149	41.4900
864	3388:08:00	0.4120	0.4149	41.4900
865	3392:08:00	0.4120	0.4150	41.5000
866	3396:07:59	0.4121	0.4150	41.5000
867	3400:07:58	0.4122	0.4151	41.5100
868	3404:07:58	0.4122	0.4152	41.5200
869	3408:07:57	0.4123	0.4152	41.5200
870	3412:07:57	0.4123	0.4153	41.5300
871	3416:07:56	0.4124	0.4153	41.5300

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

872	3420:07:55	0.4124	0.4154	41.5400
873	3424:07:55	0.4125	0.4154	41.5400
874	3428:07:54	0.4125	0.4155	41.5500
875	3432:07:54	0.4126	0.4155	41.5500
876	3436:07:53	0.4126	0.4155	41.5500
877	3440:07:53	0.4127	0.4156	41.5600
878	3444:07:52	0.4127	0.4156	41.5600
879	3448:07:51	0.4127	0.4157	41.5700
880	3452:07:51	0.4128	0.4157	41.5700
881	3456:07:50	0.4128	0.4158	41.5800
882	3460:07:50	0.4129	0.4158	41.5800
883	3464:07:49	0.4129	0.4159	41.5900
884	3468:07:49	0.4130	0.4159	41.5900
885	3472:07:48	0.4130	0.4159	41.5900
886	3476:07:47	0.4131	0.4160	41.6000
887	3480:07:47	0.4131	0.4160	41.6000
888	3484:07:46	0.4131	0.4161	41.6100
889	3488:07:46	0.4132	0.4161	41.6100
890	3492:07:45	0.4132	0.4162	41.6200
891	3496:07:45	0.4133	0.4162	41.6200
892	3500:07:44	0.4133	0.4163	41.6300
893	3504:07:43	0.4134	0.4163	41.6300
894	3508:07:43	0.4134	0.4164	41.6400
895	3512:07:42	0.4135	0.4164	41.6400
896	3516:07:42	0.4135	0.4164	41.6400
897	3520:07:41	0.4136	0.4165	41.6500
898	3524:07:40	0.4136	0.4165	41.6500
899	3528:07:40	0.4136	0.4166	41.6600
900	3532:07:39	0.4137	0.4166	41.6600
901	3536:07:39	0.4138	0.4167	41.6700
902	3540:07:38	0.4138	0.4168	41.6800
903	3544:07:38	0.4139	0.4169	41.6900
904	3548:07:37	0.4140	0.4169	41.6900
905	3552:07:36	0.4141	0.4170	41.7000
906	3556:07:36	0.4142	0.4171	41.7100
907	3560:07:35	0.4142	0.4172	41.7200
908	3564:07:35	0.4143	0.4173	41.7300
909	3568:07:34	0.4144	0.4173	41.7300

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

910	3572:07:34	0.4145	0.4174	41.7400
911	3576:07:33	0.4146	0.4175	41.7500
912	3580:07:32	0.4146	0.4176	41.7600
913	3584:07:32	0.4147	0.4177	41.7700
914	3588:07:31	0.4148	0.4177	41.7700
915	3592:07:31	0.4149	0.4178	41.7800
916	3596:07:30	0.4150	0.4179	41.7900
917	3600:07:30	0.4150	0.4180	41.8000
918	3604:07:29	0.4151	0.4181	41.8100
919	3608:07:28	0.4152	0.4181	41.8100
920	3612:07:28	0.4153	0.4182	41.8200
921	3616:07:27	0.4154	0.4183	41.8300
922	3620:07:27	0.4154	0.4184	41.8400
923	3624:07:26	0.4155	0.4185	41.8500
924	3628:07:26	0.4156	0.4185	41.8500
925	3632:07:25	0.4157	0.4186	41.8600
926	3636:07:24	0.4158	0.4187	41.8700
927	3640:07:24	0.4158	0.4188	41.8800
928	3644:07:23	0.4159	0.4189	41.8900
929	3648:07:23	0.4160	0.4189	41.8900
930	3652:07:22	0.4161	0.4190	41.9000
931	3656:07:21	0.4162	0.4191	41.9100
932	3660:07:21	0.4162	0.4192	41.9200
933	3664:07:20	0.4163	0.4193	41.9300
934	3668:07:20	0.4164	0.4193	41.9300
935	3672:07:19	0.4165	0.4194	41.9400
936	3676:07:19	0.4166	0.4195	41.9500
937	3680:07:18	0.4166	0.4196	41.9600
938	3684:07:17	0.4167	0.4197	41.9700
939	3688:07:17	0.4168	0.4197	41.9700
940	3692:07:16	0.4169	0.4198	41.9800
941	3696:07:16	0.4170	0.4199	41.9900
942	3700:07:15	0.4170	0.4200	42.0000
943	3704:07:15	0.4171	0.4201	42.0100
944	3708:07:14	0.4172	0.4201	42.0100
945	3712:07:13	0.4173	0.4202	42.0200
946	3716:07:13	0.4174	0.4203	42.0300
947	3720:07:12	0.4174	0.4204	42.0400

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

948	3724:07:12	0.4175	0.4205	42.0500
949	3728:07:11	0.4176	0.4205	42.0500
950	3732:07:11	0.4177	0.4206	42.0600
951	3736:07:10	0.4178	0.4207	42.0700
952	3740:07:09	0.4178	0.4208	42.0800
953	3744:07:09	0.4179	0.4209	42.0900
954	3748:07:08	0.4180	0.4209	42.0900
955	3752:07:08	0.4181	0.4210	42.1000
956	3756:07:07	0.4182	0.4211	42.1100
957	3760:07:07	0.4182	0.4211	42.1100
958	3764:07:06	0.4182	0.4212	42.1200
959	3768:07:05	0.4183	0.4212	42.1200
960	3772:07:05	0.4183	0.4213	42.1300
961	3776:07:04	0.4184	0.4213	42.1300
962	3780:07:04	0.4184	0.4213	42.1300
963	3784:07:03	0.4184	0.4214	42.1400
964	3788:07:02	0.4185	0.4214	42.1400
965	3792:07:02	0.4185	0.4215	42.1500
966	3796:07:01	0.4186	0.4215	42.1500
967	3800:07:01	0.4186	0.4215	42.1500
968	3804:07:00	0.4186	0.4216	42.1600
969	3808:07:00	0.4187	0.4216	42.1600
970	3812:06:59	0.4187	0.4217	42.1700
971	3816:06:58	0.4188	0.4217	42.1700
972	3820:06:58	0.4188	0.4217	42.1700
973	3824:06:57	0.4188	0.4218	42.1800
974	3828:06:57	0.4189	0.4218	42.1800
975	3832:06:56	0.4189	0.4219	42.1900
976	3836:06:56	0.4190	0.4219	42.1900
977	3840:06:55	0.4190	0.4219	42.1900
978	3844:06:54	0.4190	0.4220	42.2000
979	3848:06:54	0.4191	0.4220	42.2000
980	3852:06:53	0.4191	0.4221	42.2100
981	3856:06:53	0.4192	0.4221	42.2100
982	3860:06:52	0.4192	0.4221	42.2100
983	3864:06:52	0.4192	0.4222	42.2200
984	3868:06:51	0.4193	0.4222	42.2200
985	3872:06:50	0.4193	0.4223	42.2300

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

986	3876:06:50	0.4194	0.4223	42.2300
987	3880:06:49	0.4194	0.4223	42.2300
988	3884:06:49	0.4194	0.4224	42.2400
989	3888:06:48	0.4195	0.4224	42.2400
990	3892:06:48	0.4195	0.4225	42.2500
991	3896:06:47	0.4196	0.4225	42.2500
992	3900:06:46	0.4196	0.4225	42.2500
993	3904:06:46	0.4196	0.4226	42.2600
994	3908:06:45	0.4197	0.4226	42.2600
995	3912:06:45	0.4197	0.4227	42.2700
996	3916:06:44	0.4198	0.4227	42.2700
997	3920:06:43	0.4198	0.4227	42.2700
998	3924:06:43	0.4198	0.4228	42.2800
999	3928:06:42	0.4199	0.4228	42.2800
1000	3932:06:42	0.4199	0.4229	42.2900
1001	3936:06:41	0.4200	0.4229	42.2900
1002	3940:06:41	0.4200	0.4229	42.2900
1003	3944:06:40	0.4201	0.4230	42.3000
1004	3948:06:39	0.4201	0.4231	42.3100
1005	3952:06:39	0.4202	0.4231	42.3100
1006	3956:06:38	0.4203	0.4232	42.3200
1007	3960:06:38	0.4203	0.4233	42.3300
1008	3964:06:37	0.4204	0.4234	42.3400
1009	3968:06:37	0.4205	0.4234	42.3400
1010	3972:06:36	0.4205	0.4235	42.3500
1011	3976:06:35	0.4206	0.4236	42.3600
1012	3980:06:35	0.4207	0.4236	42.3600
1013	3984:06:34	0.4208	0.4237	42.3700
1014	3988:06:34	0.4208	0.4238	42.3800
1015	3992:06:33	0.4209	0.4238	42.3800
1016	3996:06:33	0.4210	0.4239	42.3900
1017	4000:06:32	0.4210	0.4240	42.4000
1018	4004:06:31	0.4211	0.4240	42.4000
1019	4008:06:31	0.4212	0.4241	42.4100
1020	4012:06:30	0.4212	0.4242	42.4200
1021	4016:06:30	0.4213	0.4242	42.4200
1022	4020:06:29	0.4214	0.4243	42.4300
1023	4024:06:28	0.4214	0.4244	42.4400

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

1024	4028:06:28	0.4215	0.4244	42.4400
1025	4032:06:27	0.4215	0.4245	42.4500
1026	4036:06:27	0.4216	0.4245	42.4500
1027	4040:06:26	0.4216	0.4245	42.4500
1028	4044:06:26	0.4216	0.4246	42.4600
1029	4048:06:25	0.4217	0.4246	42.4600
1030	4052:06:24	0.4217	0.4247	42.4700
1031	4056:06:24	0.4218	0.4247	42.4700
1032	4060:06:23	0.4218	0.4247	42.4700
1033	4064:06:23	0.4218	0.4248	42.4800
1034	4068:06:22	0.4219	0.4248	42.4800
1035	4072:06:22	0.4219	0.4249	42.4900
1036	4076:06:21	0.4220	0.4249	42.4900
1037	4080:06:20	0.4220	0.4249	42.4900
1038	4084:06:20	0.4220	0.4250	42.5000
1039	4088:06:19	0.4221	0.4250	42.5000
1040	4092:06:19	0.4221	0.4251	42.5100
1041	4096:06:18	0.4222	0.4251	42.5100
1042	4100:06:18	0.4223	0.4252	42.5200
1043	4104:06:17	0.4224	0.4253	42.5300
1044	4108:06:16	0.4225	0.4254	42.5400
1045	4112:06:16	0.4225	0.4254	42.5400
1046	4116:06:15	0.4225	0.4255	42.5500
1047	4120:06:15	0.4226	0.4255	42.5500
1048	4124:06:14	0.4226	0.4256	42.5600
1049	4128:06:14	0.4227	0.4256	42.5600
1050	4132:06:13	0.4227	0.4256	42.5600
1051	4136:06:12	0.4227	0.4257	42.5700
1052	4140:06:12	0.4228	0.4257	42.5700
1053	4144:06:11	0.4228	0.4258	42.5800
1054	4148:06:11	0.4229	0.4258	42.5800
1055	4152:06:10	0.4229	0.4258	42.5800
1056	4156:06:09	0.4229	0.4259	42.5900
1057	4160:06:09	0.4230	0.4259	42.5900
1058	4164:06:08	0.4230	0.4260	42.6000
1059	4168:06:08	0.4231	0.4260	42.6000
1060	4172:06:07	0.4231	0.4260	42.6000
1061	4176:06:07	0.4231	0.4261	42.6100

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

1062	4180:06:06	0.4232	0.4261	42.6100
1063	4184:06:05	0.4232	0.4262	42.6200
1064	4188:06:05	0.4233	0.4262	42.6200
1065	4192:06:04	0.4233	0.4262	42.6200
1066	4196:06:04	0.4233	0.4263	42.6300
1067	4200:06:03	0.4234	0.4263	42.6300
1068	4204:06:03	0.4234	0.4264	42.6400
1069	4208:06:02	0.4235	0.4264	42.6400
1070	4212:06:01	0.4235	0.4264	42.6400
1071	4216:06:01	0.4235	0.4265	42.6500
1072	4220:06:00	0.4236	0.4265	42.6500
1073	4224:06:00	0.4236	0.4266	42.6600
1074	4228:05:59	0.4237	0.4266	42.6600
1075	4232:05:59	0.4237	0.4266	42.6600
1076	4236:05:58	0.4237	0.4267	42.6700
1077	4240:05:57	0.4238	0.4267	42.6700
1078	4244:05:57	0.4238	0.4268	42.6800
1079	4248:05:56	0.4239	0.4268	42.6800
1080	4252:05:56	0.4239	0.4268	42.6800
1081	4256:05:55	0.4239	0.4269	42.6900
1082	4260:05:55	0.4240	0.4269	42.6900
1083	4264:05:54	0.4240	0.4270	42.7000
1084	4268:05:53	0.4241	0.4270	42.7000
1085	4272:05:53	0.4241	0.4270	42.7000
1086	4276:05:52	0.4241	0.4271	42.7100
1087	4280:05:52	0.4242	0.4271	42.7100
1088	4284:05:51	0.4242	0.4272	42.7200
1089	4288:05:50	0.4243	0.4272	42.7200
1090	4292:05:50	0.4243	0.4272	42.7200
1091	4296:05:49	0.4243	0.4273	42.7300
1092	4300:05:49	0.4244	0.4273	42.7300
1093	4304:05:48	0.4244	0.4274	42.7400
1094	4308:05:48	0.4245	0.4274	42.7400
1095	4312:05:47	0.4245	0.4274	42.7400
1096	4316:05:46	0.4245	0.4275	42.7500
1097	4320:05:46	0.4246	0.4275	42.7500
1098	4324:05:45	0.4246	0.4276	42.7600
1099	4328:05:45	0.4247	0.4276	42.7600

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

1100	4332:05:44	0.4247	0.4276	42.7600
1101	4336:05:44	0.4247	0.4277	42.7700
1102	4340:05:43	0.4248	0.4277	42.7700
1103	4344:05:42	0.4248	0.4278	42.7800
1104	4348:05:42	0.4249	0.4278	42.7800
1105	4352:05:41	0.4249	0.4278	42.7800
1106	4356:05:41	0.4249	0.4279	42.7900
1107	4360:05:40	0.4250	0.4279	42.7900
1108	4364:05:40	0.4250	0.4280	42.8000
1109	4368:05:39	0.4251	0.4280	42.8000
1110	4372:05:38	0.4251	0.4280	42.8000
1111	4376:05:38	0.4251	0.4281	42.8100
1112	4380:05:37	0.4252	0.4281	42.8100
1113	4384:05:37	0.4252	0.4282	42.8200
1114	4388:05:36	0.4253	0.4282	42.8200
1115	4392:05:36	0.4253	0.4282	42.8200
1116	4396:05:35	0.4253	0.4283	42.8300
1117	4400:05:34	0.4254	0.4283	42.8300
1118	4404:05:34	0.4254	0.4284	42.8400
1119	4408:05:33	0.4255	0.4284	42.8400
1120	4412:05:33	0.4255	0.4284	42.8400
1121	4416:05:32	0.4255	0.4285	42.8500
1122	4420:05:31	0.4256	0.4285	42.8500
1123	4424:05:31	0.4256	0.4286	42.8600
1124	4428:05:30	0.4257	0.4286	42.8600
1125	4432:05:30	0.4257	0.4286	42.8600
1126	4436:05:29	0.4257	0.4287	42.8700
1127	4440:05:29	0.4258	0.4287	42.8700
1128	4444:05:28	0.4258	0.4288	42.8800
1129	4448:05:27	0.4259	0.4288	42.8800
1130	4452:05:27	0.4259	0.4288	42.8800
1131	4456:05:26	0.4259	0.4289	42.8900
1132	4460:05:26	0.4260	0.4289	42.8900
1133	4464:05:25	0.4260	0.4290	42.9000
1134	4468:05:25	0.4261	0.4290	42.9000
1135	4472:05:24	0.4261	0.4290	42.9000
1136	4476:05:23	0.4261	0.4291	42.9100
1137	4480:05:23	0.4262	0.4291	42.9100

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

1138	4484:05:22	0.4262	0.4292	42.9200
1139	4488:05:22	0.4263	0.4292	42.9200
1140	4492:05:21	0.4263	0.4292	42.9200
1141	4496:05:21	0.4263	0.4293	42.9300
1142	4500:05:20	0.4264	0.4293	42.9300
1143	4504:05:19	0.4264	0.4294	42.9400
1144	4508:05:19	0.4265	0.4294	42.9400
1145	4512:05:18	0.4265	0.4294	42.9400
1146	4516:05:18	0.4265	0.4295	42.9500
1147	4520:05:17	0.4266	0.4295	42.9500
1148	4524:05:16	0.4266	0.4296	42.9600
1149	4528:05:16	0.4267	0.4296	42.9600
1150	4532:05:15	0.4267	0.4296	42.9600
1151	4536:05:15	0.4267	0.4297	42.9700
1152	4540:05:14	0.4268	0.4297	42.9700
1153	4544:05:14	0.4268	0.4298	42.9800
1154	4548:05:13	0.4269	0.4298	42.9800
1155	4552:05:12	0.4269	0.4298	42.9800
1156	4556:05:12	0.4269	0.4299	42.9900
1157	4560:05:11	0.4270	0.4299	42.9900
1158	4564:05:11	0.4270	0.4299	42.9900
1159	4568:05:10	0.4270	0.4300	43.0000
1160	4572:05:10	0.4271	0.4300	43.0000
1161	4576:05:09	0.4271	0.4301	43.0100
1162	4580:05:08	0.4271	0.4301	43.0100
1163	4584:05:08	0.4272	0.4301	43.0100
1164	4588:05:07	0.4272	0.4302	43.0200
1165	4592:05:07	0.4273	0.4302	43.0200
1166	4596:05:06	0.4273	0.4302	43.0200
1167	4600:05:06	0.4273	0.4303	43.0300
1168	4604:05:05	0.4274	0.4303	43.0300
1169	4608:05:04	0.4274	0.4303	43.0300
1170	4612:05:04	0.4274	0.4304	43.0400
1171	4616:05:03	0.4275	0.4304	43.0400
1172	4620:05:03	0.4275	0.4304	43.0400
1173	4624:05:02	0.4275	0.4305	43.0500
1174	4628:05:02	0.4276	0.4305	43.0500
1175	4632:05:01	0.4276	0.4306	43.0600

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

1176	4636:05:00	0.4277	0.4306	43.0600
1177	4640:05:00	0.4277	0.4306	43.0600
1178	4644:04:59	0.4277	0.4307	43.0700
1179	4648:04:59	0.4278	0.4307	43.0700
1180	4652:04:58	0.4278	0.4307	43.0700
1181	4656:04:57	0.4278	0.4308	43.0800
1182	4660:04:57	0.4279	0.4308	43.0800
1183	4664:04:56	0.4279	0.4308	43.0800
1184	4668:04:56	0.4279	0.4309	43.0900
1185	4672:04:55	0.4280	0.4309	43.0900
1186	4676:04:55	0.4280	0.4310	43.1000
1187	4680:04:54	0.4280	0.4310	43.1000
1188	4684:04:53	0.4281	0.4310	43.1000
1189	4688:04:53	0.4281	0.4311	43.1100
1190	4692:04:52	0.4282	0.4311	43.1100
1191	4696:04:52	0.4282	0.4311	43.1100
1192	4700:04:51	0.4282	0.4312	43.1200
1193	4704:04:51	0.4283	0.4312	43.1200
1194	4708:04:50	0.4283	0.4312	43.1200
1195	4712:04:49	0.4283	0.4313	43.1300
1196	4716:04:49	0.4284	0.4313	43.1300
1197	4720:04:48	0.4284	0.4313	43.1300
1198	4724:04:48	0.4284	0.4314	43.1400
1199	4728:04:47	0.4285	0.4314	43.1400
1200	4732:04:47	0.4285	0.4315	43.1500
1201	4736:04:46	0.4286	0.4315	43.1500
1202	4740:04:45	0.4286	0.4316	43.1600
1203	4744:04:45	0.4287	0.4316	43.1600
1204	4748:04:44	0.4287	0.4317	43.1700
1205	4752:04:44	0.4288	0.4317	43.1700
1206	4756:04:43	0.4288	0.4318	43.1800
1207	4760:04:43	0.4289	0.4318	43.1800
1208	4764:04:42	0.4289	0.4319	43.1900
1209	4768:04:41	0.4290	0.4319	43.1900
1210	4772:04:41	0.4290	0.4320	43.2000
1211	4776:04:40	0.4291	0.4320	43.2000
1212	4780:04:40	0.4291	0.4320	43.2000
1213	4784:04:39	0.4292	0.4321	43.2100

Table C.1.7 Start of Biodegradation Waste Sample – 4.400 tsf (continued)

1214	4788:04:38	0.4292	0.4321	43.2100
1215	4792:04:38	0.4292	0.4322	43.2200
1216	4796:04:37	0.4293	0.4322	43.2200
1217	4800:04:37	0.4293	0.4323	43.2300
1218	4804:04:36	0.4294	0.4323	43.2300
1219	4808:04:36	0.4294	0.4324	43.2400
1220	4812:04:35	0.4295	0.4324	43.2400
1221	4816:04:34	0.4295	0.4325	43.2500
1222	4820:04:34	0.4296	0.4325	43.2500
1223	4824:04:33	0.4296	0.4325	43.2500
1224	4828:04:33	0.4297	0.4326	43.2600
1225	4832:04:32	0.4297	0.4326	43.2600
1226	4836:04:32	0.4297	0.4327	43.2700
1227	4840:04:31	0.4298	0.4327	43.2700
1228	4844:04:30	0.4298	0.4328	43.2800
1229	4848:04:30	0.4299	0.4328	43.2800
1230	4852:04:29	0.4299	0.4329	43.2900

Table C.2.1 End of Biodegradation Waste Sample – 0.137 tsf

0	00:00:00	0.0007	0.0000	0.0000
1	00:00:01	0.0025	0.0018	0.1800
2	00:00:02	0.0029	0.0022	0.2200
3	00:00:03	0.0032	0.0025	0.2500
4	00:00:04	0.0034	0.0027	0.2700
5	00:00:05	0.0036	0.0029	0.2900
6	00:00:06	0.0039	0.0032	0.3200
7	00:00:12	0.0046	0.0039	0.3900
8	00:00:15	0.0048	0.0041	0.4100
9	00:00:30	0.0056	0.0049	0.4900
10	00:01:00	0.0065	0.0058	0.5800
11	00:02:00	0.0073	0.0066	0.6600
12	00:05:00	0.0087	0.0080	0.8000
13	00:10:00	0.0097	0.0090	0.9000
14	00:20:02	0.0110	0.0103	1.0300
15	00:40:04	0.0123	0.0116	1.1600
16	01:00:06	0.0132	0.0125	1.2500
17	02:00:14	0.0148	0.0141	1.4100
18	04:00:27	0.0163	0.0156	1.5600
19	08:00:55	0.0177	0.0170	1.7000
20	12:01:24	0.0184	0.0177	1.7700
21	16:01:52	0.0190	0.0183	1.8300
22	20:02:20	0.0197	0.0190	1.9000
23	24:02:48	0.0203	0.0196	1.9600
24	24:59:25	0.0207	0.0200	2.0000

Table C.2.2 End of Biodegradation Waste Sample – 0.275 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.0207	0.0200	2.0000
1	00:00:01	0.0255	0.0248	2.4800
2	00:00:02	0.0267	0.0260	2.6000
3	00:00:03	0.0276	0.0269	2.6900
4	00:00:04	0.0282	0.0275	2.7500
5	00:00:05	0.0288	0.0281	2.8100
6	00:00:06	0.0292	0.0285	2.8500
7	00:00:12	0.0310	0.0303	3.0300
8	00:00:15	0.0316	0.0309	3.0900
9	00:00:30	0.0336	0.0329	3.2900
10	00:01:00	0.0354	0.0347	3.4700
11	00:02:01	0.0375	0.0368	3.6800
12	00:05:01	0.0401	0.0394	3.9400
13	00:10:01	0.0420	0.0413	4.1300
14	00:20:03	0.0441	0.0434	4.3400
15	00:40:05	0.0465	0.0458	4.5800
16	01:00:07	0.0479	0.0472	4.7200
17	02:00:14	0.0503	0.0496	4.9600
18	04:00:28	0.0527	0.0520	5.2000
19	08:00:57	0.0549	0.0542	5.4200
20	12:01:25	0.0561	0.0554	5.5400
21	16:01:52	0.0575	0.0568	5.6800
22	20:02:21	0.0591	0.0584	5.8400
23	23:19:55	0.0601	0.0594	5.9400

Table C.2.3 End of Biodegradation Waste Sample – 0.550 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.0601	0.0594	5.9400
1	00:00:01	0.0664	0.0657	6.5700
2	00:00:02	0.0680	0.0673	6.7300
3	00:00:03	0.0690	0.0683	6.8300
4	00:00:04	0.0699	0.0692	6.9200
5	00:00:05	0.0705	0.0698	6.9800
6	00:00:06	0.0712	0.0705	7.0500
7	00:00:12	0.0735	0.0728	7.2800
8	00:00:15	0.0743	0.0736	7.3600
9	00:00:30	0.0768	0.0761	7.6100
10	00:01:00	0.0793	0.0786	7.8600
11	00:02:00	0.0818	0.0811	8.1100
12	00:05:00	0.0853	0.0846	8.4600
13	00:10:01	0.0879	0.0872	8.7200
14	00:20:02	0.0906	0.0899	8.9900
15	00:40:04	0.0935	0.0928	9.2800
16	01:00:07	0.0952	0.0945	9.4500
17	02:00:14	0.0983	0.0976	9.7600
18	04:00:28	0.1012	0.1005	10.0500
19	08:00:57	0.1040	0.1033	10.3300
20	12:01:25	0.1056	0.1049	10.4900
21	16:01:53	0.1070	0.1063	10.6300
22	20:02:21	0.1082	0.1075	10.7500
23	24:02:50	0.1095	0.1088	10.8800
24	28:03:18	0.1104	0.1097	10.9700
25	32:03:46	0.1110	0.1103	11.0300
26	36:04:14	0.1115	0.1108	11.0800
27	40:04:43	0.1121	0.1114	11.1400
28	44:05:10	0.1128	0.1121	11.2100
29	48:05:34	0.1134	0.1127	11.2700
30	52:06:00	0.1139	0.1132	11.3200
31	56:06:28	0.1144	0.1137	11.3700
32	60:06:56	0.1146	0.1139	11.3900
33	64:07:24	0.1150	0.1143	11.4300
34	68:07:53	0.1154	0.1147	11.4700
35	71:01:34	0.1160	0.1153	11.5300

Table C.2.4 End of Biodegradation Waste Sample – 1.100 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.1160	0.1153	11.5300
1	00:00:01	0.1219	0.1212	12.1200
2	00:00:02	0.1232	0.1225	12.2500
3	00:00:03	0.1241	0.1234	12.3400
4	00:00:04	0.1248	0.1241	12.4100
5	00:00:05	0.1253	0.1246	12.4600
6	00:00:06	0.1257	0.1250	12.5000
7	00:00:12	0.1278	0.1271	12.7100
8	00:00:15	0.1284	0.1277	12.7700
9	00:00:30	0.1306	0.1299	12.9900
10	00:01:00	0.1330	0.1323	13.2300
11	00:02:01	0.1354	0.1347	13.4700
12	00:05:01	0.1387	0.1380	13.8000
13	00:10:01	0.1413	0.1406	14.0600
14	00:20:03	0.1440	0.1433	14.3300
15	00:40:05	0.1469	0.1462	14.6200
16	01:00:07	0.1486	0.1479	14.7900
17	02:00:14	0.1516	0.1509	15.0900
18	04:00:28	0.1545	0.1538	15.3800
19	08:00:56	0.1572	0.1565	15.6500
20	12:01:25	0.1586	0.1579	15.7900
21	16:01:53	0.1598	0.1591	15.9100
22	20:02:19	0.1609	0.1602	16.0200
23	24:02:46	0.1619	0.1612	16.1200
24	28:03:15	0.1627	0.1620	16.2000
25	32:03:42	0.1633	0.1626	16.2600
26	36:04:11	0.1637	0.1630	16.3000
27	40:04:39	0.1641	0.1634	16.3400
28	44:05:07	0.1647	0.1640	16.4000
29	48:05:36	0.1651	0.1644	16.4400
30	52:06:04	0.1656	0.1649	16.4900
31	56:06:32	0.1659	0.1652	16.5200
32	60:07:01	0.1663	0.1656	16.5600
33	60:35:59	0.1663	0.1656	16.5600

Table C.2.5 End of Biodegradation Waste Sample – 2.200 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.1663	0.1656	16.5600
1	00:00:01	0.1727	0.1720	17.2000
2	00:00:02	0.1738	0.1731	17.3100
3	00:00:03	0.1745	0.1738	17.3800
4	00:00:04	0.1751	0.1744	17.4400
5	00:00:05	0.1754	0.1747	17.4700
6	00:00:06	0.1758	0.1751	17.5100
7	00:00:12	0.1773	0.1766	17.6600
8	00:00:15	0.1778	0.1771	17.7100
9	00:00:30	0.1797	0.1790	17.9000
10	00:01:00	0.1817	0.1810	18.1000
11	00:02:00	0.1840	0.1833	18.3300
12	00:05:01	0.1873	0.1866	18.6600
13	00:10:00	0.1900	0.1893	18.9300
14	00:20:03	0.1929	0.1922	19.2200
15	00:40:05	0.1959	0.1952	19.5200
16	01:00:06	0.1976	0.1969	19.6900
17	02:00:14	0.2008	0.2001	20.0100
18	04:00:28	0.2045	0.2038	20.3800
19	08:00:56	0.2089	0.2082	20.8200
20	12:01:24	0.2116	0.2109	21.0900
21	16:01:52	0.2129	0.2122	21.2200
22	20:02:21	0.2138	0.2131	21.3100
23	24:02:49	0.2145	0.2138	21.3800
24	28:03:17	0.2152	0.2145	21.4500
25	32:03:45	0.2158	0.2151	21.5100
26	33:26:09	0.2160	0.2153	21.5300

Table C.2.6 End of Biodegradation Waste Sample – 4.400 tsf

Index	Time	Displacement [in.]	Settlement [in.]	Axial Strain [%]
0	00:00:00	0.2160	0.2153	21.5300
1	00:00:01	0.2161	0.2154	21.5400
2	00:00:02	0.2161	0.2154	21.5400
3	00:00:03	0.2161	0.2154	21.5400
4	00:00:04	0.2161	0.2154	21.5400
5	00:00:05	0.2161	0.2154	21.5400
6	00:00:06	0.2161	0.2154	21.5400
7	00:00:12	0.2281	0.2274	22.7400
8	00:00:15	0.2295	0.2288	22.8800
9	00:00:30	0.2329	0.2322	23.2200
10	00:01:00	0.2361	0.2354	23.5400
11	00:02:00	0.2393	0.2386	23.8600
12	00:05:00	0.2437	0.2430	24.3000
13	00:10:01	0.2471	0.2464	24.6400
14	00:20:02	0.2505	0.2498	24.9800
15	00:40:04	0.2538	0.2531	25.3100
16	01:00:06	0.2559	0.2552	25.5200
17	02:00:14	0.2593	0.2586	25.8600
18	04:00:28	0.2626	0.2619	26.1900
19	08:00:57	0.2657	0.2650	26.5000
20	12:01:24	0.2672	0.2665	26.6500
21	16:01:52	0.2682	0.2675	26.7500
22	20:02:21	0.2693	0.2686	26.8600
23	24:02:49	0.2707	0.2700	27.0000
24	28:03:17	0.2719	0.2712	27.1200
26	36:04:13	0.2729	0.2722	27.2200
27	40:04:36	0.2733	0.2726	27.2600
28	44:05:04	0.2736	0.2729	27.2900
29	48:05:33	0.2738	0.2731	27.3100
30	52:06:01	0.2742	0.2735	27.3500
31	56:06:29	0.2744	0.2737	27.3700
32	60:06:58	0.2745	0.2738	27.3800
33	64:07:25	0.2746	0.2739	27.3900
34	68:07:54	0.2748	0.2741	27.4100
35	72:08:22	0.2752	0.2745	27.4500
36	76:08:50	0.2754	0.2747	27.4700

Table C.2.7 End of Biodegradation Waste Sample – 4.400 tsf (continued)

37	80:09:19	0.2757	0.2750	27.5000
38	84:09:47	0.2759	0.2752	27.5200
39	88:10:15	0.2760	0.2753	27.5300
40	92:10:44	0.2761	0.2754	27.5400
41	96:11:12	0.2763	0.2756	27.5600
42	100:11:4	0.2767	0.2760	27.6000
43	104:11:3	0.2768	0.2761	27.6100
44	108:11:3	0.2769	0.2762	27.6200
45	112:11:3	0.2771	0.2764	27.6400
46	116:11:3	0.2771	0.2764	27.6400
47	120:11:3	0.2772	0.2765	27.6500
48	124:11:3	0.2774	0.2767	27.6700
49	128:11:3	0.2776	0.2769	27.6900
50	132:11:3	0.2777	0.2770	27.7000
51	136:11:3	0.2777	0.2770	27.7000
52	140:11:3	0.2777	0.2770	27.7000
53	144:11:3	0.2778	0.2771	27.7100
54	148:11:3	0.2780	0.2773	27.7300
55	152:11:3	0.2783	0.2776	27.7600
56	156:11:3	0.2784	0.2777	27.7700
57	160:11:3	0.2784	0.2777	27.7700
58	164:11:3	0.2784	0.2777	27.7700
59	168:11:3	0.2785	0.2778	27.7800
60	172:11:3	0.2787	0.2780	27.8000
61	176:11:3	0.2788	0.2781	27.8100
62	180:11:3	0.2790	0.2783	27.8300
63	184:11:3	0.2790	0.2783	27.8300
64	188:11:3	0.2791	0.2784	27.8400
65	192:11:3	0.2792	0.2785	27.8500
66	196:11:3	0.2793	0.2786	27.8600
67	200:11:3	0.2794	0.2787	27.8700
68	204:11:3	0.2795	0.2788	27.8800
69	208:11:3	0.2795	0.2788	27.8800
70	212:11:3	0.2795	0.2788	27.8800
71	216:11:3	0.2797	0.2790	27.9000
72	220:11:3	0.2798	0.2791	27.9100
73	224:11:3	0.2799	0.2792	27.9200
74	228:11:3	0.2800	0.2793	27.9300

Table C.2.7 End of Biodegradation Waste Sample – 4.400 tsf (continued)

75	232:11:3	0.2800	0.2793	27.9300
76	236:11:3	0.2801	0.2794	27.9400
77	240:11:3	0.2802	0.2795	27.9500
78	244:11:3	0.2803	0.2796	27.9600
79	248:11:3	0.2804	0.2797	27.9700
80	252:11:3	0.2805	0.2798	27.9800
81	256:11:3	0.2806	0.2799	27.9900
82	260:11:3	0.2806	0.2799	27.9900
83	264:11:3	0.2807	0.2800	28.0000
84	268:11:3	0.2809	0.2802	28.0200
85	272:11:3	0.2809	0.2802	28.0200
86	276:11:3	0.2810	0.2803	28.0300
87	280:11:3	0.2811	0.2804	28.0400
88	284:11:3	0.2811	0.2804	28.0400
89	288:11:3	0.2811	0.2804	28.0400
90	292:11:3	0.2812	0.2805	28.0500
91	296:11:3	0.2813	0.2806	28.0600
92	300:11:3	0.2814	0.2807	28.0700
93	304:11:3	0.2815	0.2808	28.0800
94	308:11:3	0.2815	0.2808	28.0800
95	312:11:3	0.2815	0.2808	28.0800
96	316:11:3	0.2816	0.2809	28.0900
97	320:11:3	0.2816	0.2809	28.0900
98	324:11:3	0.2816	0.2809	28.0900
99	328:11:3	0.2817	0.2810	28.1000
100	332:11:3	0.2817	0.2810	28.1000
101	336:11:3	0.2817	0.2810	28.1000
102	340:11:3	0.2818	0.2811	28.1100
103	344:11:3	0.2818	0.2811	28.1100
104	348:11:3	0.2819	0.2812	28.1200
105	352:11:3	0.2819	0.2812	28.1200
106	356:11:3	0.2819	0.2812	28.1200
107	360:11:3	0.2819	0.2812	28.1200
108	364:11:3	0.2820	0.2813	28.1300
109	368:11:3	0.2821	0.2814	28.1400
110	372:11:3	0.2822	0.2815	28.1500
111	376:11:3	0.2822	0.2815	28.1500
112	380:11:3	0.2823	0.2816	28.1600

Table C.2.7 End of Biodegradation Waste Sample – 4.400 tsf (continued)

113	384:11:3	0.2824	0.2817	28.1700
114	388:11:3	0.2825	0.2818	28.1800
115	392:11:3	0.2825	0.2818	28.1800
116	396:11:3	0.2826	0.2819	28.1900
117	400:11:3	0.2827	0.2820	28.2000
118	404:11:3	0.2827	0.2820	28.2000
119	408:11:3	0.2828	0.2821	28.2100
120	412:11:3	0.2830	0.2823	28.2300
121	416:11:3	0.2831	0.2824	28.2400
122	420:11:3	0.2832	0.2825	28.2500
123	424:11:3	0.2832	0.2825	28.2500
124	428:11:3	0.2833	0.2826	28.2600
125	432:11:3	0.2833	0.2826	28.2600
126	436:11:3	0.2834	0.2827	28.2700
127	440:11:3	0.2835	0.2828	28.2800
128	444:11:3	0.2836	0.2829	28.2900
129	448:11:3	0.2836	0.2829	28.2900
130	452:11:3	0.2836	0.2829	28.2900
131	456:11:3	0.2837	0.2830	28.3000
132	460:11:3	0.2838	0.2831	28.3100
133	464:11:3	0.2838	0.2831	28.3100
134	468:11:3	0.2839	0.2832	28.3200
135	472:11:3	0.2839	0.2832	28.3200
136	476:11:3	0.2839	0.2832	28.3200
137	480:11:3	0.2840	0.2833	28.3300
138	484:11:3	0.2840	0.2833	28.3300
139	488:11:3	0.2840	0.2833	28.3300
140	492:11:3	0.2840	0.2833	28.3300
141	496:11:3	0.2840	0.2833	28.3300
142	500:11:3	0.2841	0.2834	28.3400
143	504:11:3	0.2841	0.2834	28.3400
144	508:11:3	0.2841	0.2834	28.3400
145	512:11:3	0.2841	0.2834	28.3400
146	516:11:3	0.2842	0.2835	28.3500
147	520:11:3	0.2842	0.2835	28.3500
148	524:11:3	0.2842	0.2835	28.3500
149	528:11:3	0.2842	0.2835	28.3500
150	532:11:3	0.2843	0.2836	28.3600

Table C.2.7 End of Biodegradation Waste Sample – 4.400 tsf (continued)

151	536:11:3	0.2843	0.2836	28.3600
152	540:11:3	0.2844	0.2837	28.3700
153	544:11:3	0.2844	0.2837	28.3700
154	548:11:3	0.2844	0.2837	28.3700
155	552:11:3	0.2845	0.2838	28.3800
156	556:11:3	0.2846	0.2839	28.3900
157	560:11:3	0.2847	0.2840	28.4000
158	564:11:3	0.2847	0.2840	28.4000
159	568:11:3	0.2847	0.2840	28.4000
160	572:11:3	0.2847	0.2840	28.4000
161	576:11:3	0.2848	0.2841	28.4100
162	580:11:3	0.2848	0.2841	28.4100
163	584:11:3	0.2848	0.2841	28.4100
164	588:11:3	0.2849	0.2842	28.4200
165	592:11:3	0.2849	0.2842	28.4200
166	596:11:3	0.2849	0.2842	28.4200
167	596:11:3	0.2849	0.2842	28.4200
168	600:11:03	0.2849	0.2842	28.4200
169	604:11:03	0.2849	0.2842	28.4200
170	608:11:03	0.2849	0.2842	28.4200
171	612:11:03	0.2850	0.2843	28.4300
172	616:11:03	0.2850	0.2843	28.4300
173	620:11:03	0.2850	0.2843	28.4300
174	624:11:03	0.2850	0.2843	28.4300
175	628:11:03	0.2850	0.2843	28.4300
176	632:11:03	0.2851	0.2844	28.4400
177	636:11:03	0.2851	0.2844	28.4400
178	640:11:03	0.2851	0.2844	28.4400
179	644:11:03	0.2851	0.2844	28.4400
180	648:11:03	0.2852	0.2845	28.4500
181	652:11:03	0.2853	0.2846	28.4600
182	656:11:03	0.2854	0.2847	28.4700
183	660:11:03	0.2854	0.2847	28.4700
184	664:11:03	0.2854	0.2847	28.4700
185	668:11:03	0.2854	0.2847	28.4700
186	672:11:03	0.2855	0.2848	28.4800
187	676:11:03	0.2856	0.2849	28.4900
188	680:11:03	0.2856	0.2849	28.4900

Table C.2.7 End of Biodegradation Waste Sample – 4.400 tsf (continued)

189	688:11:03	0.2856	0.2849	28.4900
190	692:11:03	0.2856	0.2849	28.4900
191	696:11:03	0.2856	0.2849	28.4900
192	700:11:03	0.2856	0.2849	28.4900
193	704:11:03	0.2857	0.2850	28.5000
194	708:11:03	0.2857	0.2850	28.5000
195	712:11:03	0.2857	0.2850	28.5000
196	716:11:03	0.2857	0.2850	28.5000
197	720:11:03	0.2857	0.2850	28.5000
198	724:11:03	0.2857	0.2850	28.5000
199	728:11:03	0.2857	0.2850	28.5000
200	732:11:03	0.2857	0.2850	28.5000
201	736:11:03	0.2857	0.2850	28.5000
202	740:11:03	0.2857	0.2850	28.5000
203	744:11:03	0.2858	0.2851	28.5100
204	748:11:03	0.2858	0.2851	28.5100
205	752:11:03	0.2859	0.2852	28.5200
206	756:11:03	0.2859	0.2852	28.5200
207	760:11:03	0.2859	0.2852	28.5200
208	764:11:03	0.2859	0.2852	28.5200
209	768:11:03	0.2859	0.2852	28.5200
210	772:11:03	0.2859	0.2852	28.5200
211	776:11:03	0.2859	0.2852	28.5200
212	780:11:03	0.2859	0.2852	28.5200
213	784:11:03	0.2859	0.2852	28.5200
214	788:11:03	0.2859	0.2852	28.5200
215	792:11:03	0.2859	0.2852	28.5200
216	796:11:03	0.2859	0.2852	28.5200
217	800:11:03	0.2859	0.2852	28.5200
218	804:11:03	0.2859	0.2852	28.5200
219	808:11:03	0.2859	0.2852	28.5200
220	812:11:03	0.2859	0.2852	28.5200
221	816:11:03	0.2859	0.2852	28.5200
222	820:11:03	0.2859	0.2852	28.5200
223	824:11:03	0.2859	0.2852	28.5200
224	828:11:03	0.2860	0.2853	28.5300
225	832:11:03	0.2860	0.2853	28.5300
226	836:11:03	0.2860	0.2853	28.5300

Table C.2.7 End of Biodegradation Waste Sample – 4.400 tsf (continued)

227	840:11:03	0.2860	0.2853	28.5300
228	844:11:03	0.2861	0.2854	28.5400
229	848:11:03	0.2861	0.2854	28.5400
230	852:11:03	0.2862	0.2855	28.5500
231	856:11:03	0.2862	0.2855	28.5500
232	860:11:03	0.2862	0.2855	28.5500
233	864:11:03	0.2862	0.2855	28.5500
234	868:11:03	0.2863	0.2856	28.5600
235	872:11:03	0.2863	0.2856	28.5600
236	876:11:03	0.2863	0.2856	28.5600
237	880:11:03	0.2863	0.2856	28.5600
238	884:11:03	0.2863	0.2856	28.5600
239	888:11:03	0.2864	0.2857	28.5700
240	892:11:03	0.2864	0.2857	28.5700
241	896:11:03	0.2864	0.2857	28.5700
242	900:11:03	0.2864	0.2857	28.5700
243	904:11:03	0.2864	0.2857	28.5700
244	908:11:03	0.2864	0.2857	28.5700
245	912:11:03	0.2865	0.2858	28.5800
246	916:11:03	0.2865	0.2858	28.5800
247	920:11:03	0.2865	0.2858	28.5800
248	924:11:03	0.2865	0.2858	28.5800
249	928:11:03	0.2865	0.2858	28.5800
250	932:11:03	0.2865	0.2858	28.5800
251	936:11:03	0.2866	0.2859	28.5900
252	940:11:03	0.2866	0.2859	28.5900
253	944:11:03	0.2866	0.2859	28.5900
254	948:11:03	0.2866	0.2859	28.5900
255	952:11:03	0.2866	0.2859	28.5900
256	956:11:03	0.2866	0.2859	28.5900
257	960:11:03	0.2866	0.2859	28.5900
258	964:11:03	0.2866	0.2859	28.5900
259	968:11:03	0.2866	0.2859	28.5900
260	972:11:03	0.2866	0.2859	28.5900
261	976:11:03	0.2866	0.2859	28.5900
262	980:11:03	0.2866	0.2859	28.5900
263	984:11:03	0.2866	0.2859	28.5900
264	988:11:03	0.2866	0.2859	28.5900

Table C.2.7 End of Biodegradation Waste Sample – 4.400 tsf (continued)

265	992:11:03	0.2866	0.2859	28.5900
266	996:11:03	0.2866	0.2859	28.5900
267	1000:11:03	0.2867	0.2860	28.6000
268	1004:11:03	0.2867	0.2860	28.6000
269	1008:11:03	0.2867	0.2860	28.6000
270	1012:11:03	0.2867	0.2860	28.6000
271	1016:11:03	0.2867	0.2860	28.6000
272	1020:11:03	0.2867	0.2860	28.6000
273	1024:11:03	0.2867	0.2860	28.6000
274	1028:11:03	0.2867	0.2860	28.6000
275	1032:11:03	0.2868	0.2861	28.6100
276	1036:11:03	0.2868	0.2861	28.6100
277	1040:11:03	0.2868	0.2861	28.6100
278	1044:11:03	0.2869	0.2862	28.6200
279	1048:11:03	0.2869	0.2862	28.6200
280	1052:11:03	0.2869	0.2862	28.6200
281	1056:11:03	0.2869	0.2862	28.6200
282	1060:11:03	0.2869	0.2862	28.6200
283	1064:11:03	0.2869	0.2862	28.6200
284	1068:11:03	0.2869	0.2862	28.6200
285	1072:11:03	0.2869	0.2862	28.6200
286	1076:11:03	0.2869	0.2862	28.6200
287	1080:11:03	0.2870	0.2863	28.6300
288	1084:11:03	0.2870	0.2863	28.6300
289	1088:11:03	0.2870	0.2863	28.6300
290	1092:11:03	0.2870	0.2863	28.6300
291	1096:11:03	0.2870	0.2863	28.6300
292	1100:11:03	0.2870	0.2863	28.6300
293	1104:11:03	0.2871	0.2864	28.6400
294	1108:11:03	0.2871	0.2864	28.6400
295	1112:11:03	0.2871	0.2864	28.6400
296	1116:11:03	0.2871	0.2864	28.6400
297	1120:11:03	0.2871	0.2864	28.6400
298	1124:11:03	0.2871	0.2864	28.6400
299	1128:11:03	0.2871	0.2864	28.6400
300	1132:11:03	0.2871	0.2864	28.6400
301	1136:11:03	0.2871	0.2864	28.6400
302	1140:11:03	0.2871	0.2864	28.6400

Table C.2.7 End of Biodegradation Waste Sample – 4.400 tsf (continued)

303	1144:11:03	0.2871	0.2864	28.6400
304	1148:11:03	0.2871	0.2864	28.6400
305	1152:11:03	0.2872	0.2865	28.6500
306	1156:11:03	0.2872	0.2865	28.6500
307	1160:11:03	0.2872	0.2865	28.6500
308	1164:11:03	0.2872	0.2865	28.6500
309	1168:11:03	0.2872	0.2865	28.6500
310	1172:11:03	0.2872	0.2865	28.6500
311	1176:11:03	0.2872	0.2865	28.6500
312	1180:11:03	0.2872	0.2865	28.6500
313	1184:11:03	0.2873	0.2866	28.6600
314	1188:11:03	0.2873	0.2866	28.6600
315	1192:11:03	0.2873	0.2866	28.6600
316	1196:11:03	0.2873	0.2866	28.6600
317	1200:11:03	0.2873	0.2866	28.6600
318	1204:11:03	0.2873	0.2866	28.6600
319	1208:11:03	0.2873	0.2866	28.6600
320	1212:11:03	0.2873	0.2866	28.6600
321	1216:11:03	0.2873	0.2866	28.6600
322	1220:11:03	0.2873	0.2866	28.6600
323	1224:11:03	0.2873	0.2866	28.6600
324	1228:11:03	0.2873	0.2866	28.6600
325	1232:11:03	0.2873	0.2866	28.6600
326	1236:11:03	0.2873	0.2866	28.6600
327	1240:11:03	0.2873	0.2866	28.6600
328	1244:11:03	0.2873	0.2866	28.6600
329	1248:11:03	0.2874	0.2867	28.6700
330	1252:11:03	0.2874	0.2867	28.6700
331	1256:11:03	0.2874	0.2867	28.6700
332	1260:11:03	0.2874	0.2867	28.6700
333	1264:11:03	0.2874	0.2867	28.6700
334	1268:11:03	0.2874	0.2867	28.6700
335	1272:11:03	0.2874	0.2867	28.6700
336	1276:11:03	0.2874	0.2867	28.6700
337	1280:11:03	0.2874	0.2867	28.6700
338	1284:11:03	0.2874	0.2867	28.6700
339	1288:11:03	0.2874	0.2867	28.6700
340	1292:11:03	0.2874	0.2867	28.6700

Table C.2.7 End of Biodegradation Waste Sample – 4.400 tsf (continued)

341	1296:11:03	0.2875	0.2868	28.6800
342	1300:11:03	0.2875	0.2868	28.6800
343	1304:11:03	0.2875	0.2868	28.6800
344	1308:11:03	0.2875	0.2868	28.6800
345	1312:11:03	0.2875	0.2868	28.6800
346	1316:11:03	0.2875	0.2868	28.6800
347	1320:11:03	0.2876	0.2869	28.6900
348	1324:11:03	0.2876	0.2869	28.6900
349	1328:11:03	0.2876	0.2869	28.6900
350	1332:11:03	0.2876	0.2869	28.6900

APPENDIX D

CALIBRATION RECORDS FOR MEASURING DEVICES

Appendix D contains calibration records for measuring devices used during the experiment. Equipment calibration was performed by the manufacturer, or an accredited laboratory to ensure conformance with equipment specifications for performance.

Figures D.1 through D.3 represent calibration certificates for the composite, readily, and moderately degradable gas flow meters, respectively, used for the experiment. Gas flow meters, Sierra Instruments model MicroTrak 101, were calibration by the manufacturer prior to use. Figures D.4 through D.8 represent calibration for gas characterization equipment, Landtec GEM2000+, which was performed at periodic intervals and performed by Pine Environmental of Windsor, New Jersey. Figures D.9 through D.16 represent calibration certificates provided by Humboldt for digital dial gauge indicators (model HM4470.10) used for consolidation testing.

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CALIBRATION CERTIFICATE

CERTIFICATE NUMBER 7117836510
PAGE 1 OF 1

Applicant/Customer	Name	VATSAL SHAH			
	Customer Address				
	City, State, Zip Code	SOUTH PLAINFIELD, NJ			
	Country	USA			
	Sales Order	144731			
	Purchase Order	VISA			
Instrument	Model	M100L-DD-1-OV1-PV2-V1-C10			
	Serial number	171510			
	Input Power	24 Volt DC			
	Full Scale	22.000		units	SCCM
	Output signal	0	5	units	0-5 Volts
	Fittings	1/8" COMP			
	Accuracy DUT (+/-)	**1.0% F/S**			
Calibration method	Calibration Station/Cal Due Date	Cal Bench Asset # 1417		July 31, 2014	
	Calibration Procedure	MFG-042.2 Rev. A			
	Software release	Cal Bench Mass Flow Calibration System, Rev. 8.00.06			
	Repeatability	+/- 0.2% of full scale			
	Temperature coefficient	+/- 0.025% of full scale per °F (0.05% of full scale per °C)			
	Pressure coefficient	0.01% of full scale per psi (0.15% of full scale per bar)			
	System ERROR	maximum systematic ERROR = 0.2%			
	DMM Asset / Cal Due Date	1576	November 13, 2013		
Calibration details	Date of calibration	August 15, 2013			
	Suggested recal date	August 15, 2014			
Calibration data	Ambient pressure	29.63	In Hg		
	Ambient temperature	70.90	°F		
	Gas	Methane			
	Calibration gas	Air			
	K-Factor	0.754			
	Reference temperature	70.0	°F		
	Reference pressure	1	ATM a.		
	Calibration pressure	**Inlet/outlet pressure**	1 PSI g.		N/A
	Calibration temperature	40-120	°F		
	Other	OUTPUT 0-5 VDC / 4-20 mA			
	Special Calibration Information	TAG# COMPOSITE-1			

Calibration results

Output	Indicated Flow	Actual Flow	Actual	Allowable
0-5 Volts	SCCM	SCCM	difference	difference
0.000	0.0000	0.0000	0.000	0.292
1.255	7.3236	7.2790	-0.045	0.292
2.507	14.6297	14.5930	-0.037	0.292
3.750	21.8833	21.8880	0.005	0.292
5.002	29.1894	29.2280	0.039	0.292

Traceability Calibration of these products is performed with equipment containing components which are tested and calibrated in accordance with ANSI/NCSL Z540 and/or ISO 17025 and are traceable to NIST. The results of this report relate only to the item calibrated or tested.

Performed by

Calibration technician ____________ **Q.C.Technician** ____________

SII form #0001 Rev. C SW: SN-0017, Rev. 1.02

Figure D.1 Calibration Record for Gas Flow Meter – Composite

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CALIBRATION CERTIFICATE

CERTIFICATE NUMBER 7117878011
PAGE 1 OF 1

Applicant/Customer	Name	VATSAL SHAH
	Customer Address	
	City, State, Zip Code	SOUTH PLAINFIELD, NJ
	Country	USA
	Sales Order	144731
	Purchase Order	VISA
Instrument	Model	M100L-DD-1-OV1-PV2-V1-C10-LF
	Serial number	171511
	Input Power	24 Volt DC
	Full Scale	10.000 units SCCM
	Output signal	0 5 units 0-5 Volts
	Fittings	1/8" COMP
	Accuracy DUT (+/-)	**1.0% F/S**
Calibration method	Calibration Station/Cal Due Date	Cal Bench Asset # 1417 July 31, 2014
	Calibration Procedure	MFG-042.2 Rev. A
	Software release	Cal Bench Mass Flow Calibration System, Rev. 8.00.06
	Repeatability	+/- 0.2% of full scale
	Temperature coefficient	+/- 0.025% of full scale per °F (0.05% of full scale per °C)
	Pressure coefficient	0.01% of full scale per psi (0.15% of full scale per bar)
	System ERROR	maximum systematic ERROR = 0.2%
	DMM Asset / Cal Due Date	1576 November 13, 2013
Calibration details	Date of calibration	August 15, 2013
	Suggested recal date	August 15, 2014
Calibration data	Ambient pressure	29.63 In Hg
	Ambient temperature	70.90 °F
	Gas	Methane
	Calibration gas	Air
	K-Factor	0.754
	Reference temperature	70.0 °F
	Reference pressure	1 ATM a.
	Calibration pressure	Inlet/outlet pressure 1 PSI g. N/A
	Calibration temperature	40-120 °F
	Other	OUTPUT 0-5 VDC / 4-20 mA
	Special Calibration Information	TAG# READILY-2

Calibration results

Output 0-5 Volts	Indicated Flow SCCM	Actual Flow SCCM	Actual difference	Allowable difference
0.000	0.0000	0.0000	0.000	0.133
1.255	3.3289	3.3150	-0.014	0.133
2.507	6.6499	6.6520	0.002	0.133
3.750	9.9469	9.9490	0.002	0.133
5.002	13.2679	13.2600	-0.008	0.133

Traceability Calibration of these products is performed with equipment containing components which are tested and calibrated in accordance with ANSI/NCSL Z540 and/or ISO 17025 and are traceable to NIST. The results of this report relate only to the item calibrated or tested.

Performed by

Calibration technician ______ **Q.C.Technician** ______

SII form #0001 Rev. C SW: SN-0017, Rev. 1.02

Figure D.2 Calibration Record for Gas Flow Meter – Readily Degradable

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CALIBRATION CERTIFICATE

CERTIFICATE NUMBER 7117919512
PAGE 1 OF 1

Applicant/Customer

Name	VATSAL SHAH
Customer Address	
City, State, Zip Code	SOUTH PLAINFIELD, NJ
Country	USA
Sales Order	144731
Purchase Order	VISA

Instrument

Model	M101L-DD-1-OV1-PV2-V1-C10			
Serial number	171512			
Input Power	24 Volt DC			
Full Scale	3.016		units	SCCM
Output signal	0	5	units	0-5 Volts
Fittings	1/8" COMP			
Accuracy DUT (+/-)	**1.0% F/S**			

Calibration method

Calibration Station/Cal Due Date	Cal Bench Asset # 1417	July 31, 2014
Calibration Procedure	MFG-042.2 Rev. A	
Software release	Cal Bench Mass Flow Calibration System, Rev. 8.00.06	
Repeatability	+/- 0.2% of full scale	
Temperature coefficient	+/- 0.025% of full scale per °F (0.05% of full scale per °C)	
Pressure coefficient	0.01% of full scale per psi (0.15% of full scale per bar)	
System ERROR	maximum systematic ERROR = 0.2%	
DMM Asset / Cal Due Date	1576	November 13, 2013

Calibration details

Date of calibration	August 15, 2013
Suggested recal date	August 15, 2014

Calibration data

Ambient pressure	29.58	In Hg	
Ambient temperature	71.40	°F	
Gas	Methane		
Calibration gas	Air		
K-Factor	0.754		
Reference temperature	70.0	°F	
Reference pressure	1	ATM a.	
Calibration pressure	**Inlet/outlet pressure**	1 PSI g.	N/A
Calibration temperature	40-120	°F	
Other	OUTPUT 0-5 VDC / 4-20 mA		
Special Calibration Information	TAG# READILY-3		

Calibration results

Output	Indicated Flow	Actual Flow	Actual	Allowable
0-5 Volts	SCCM	SCCM	difference	difference
0.000	0.0000	0.0000	0.000	0.040
1.269	1.0152	1.0220	0.007	0.040
2.515	2.0120	2.0140	0.002	0.040
3.758	3.0064	3.0090	0.003	0.040
5.008	4.0064	4.0030	-0.003	0.040

Traceability

Calibration of these products is performed with equipment containing components which are tested and calibrated in accordance with ANSI/NCSL Z540 and/or ISO 17025 and are traceable to NIST.

The results of this report relate only to the item calibrated or tested.

Performed by

Calibration technician **Q.C.Technician**

SII form #0001 Rev. C SW: SN-0017, Rev. 1.02

Figure D.3 Calibration Record for Gas Flow Meter – Moderately Degradable

INSTRUMENT CALIBRATION REPORT

Pine Environmental Services, LLC.
92 North Main St, Building 20
Windsor, NJ 08561
Toll-free: (800) 301-9663

Pine Environmental Services, Inc.

Instrument ID 16862
Description Gem 2000+
Calibrated 12/12/2013 9:24:25AM

Manufacturer CES Landtec
Model Number GEM2000+
Serial Number/ Lot Number GM12697
Location New Jersey
Department

State Certified
Status Pass
Temp °C 19
Humidity % 27

Calibration Specifications

Group # 1
Group Name Methane
Stated Accy Pct of Reading
Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
50.00 / 50.00	%Volume	50.00	%Volume	49.90	49.90	-0.20%	Pass

Group # 2
Group Name Carbon Dioxide
Stated Accy Pct of Reading
Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
35.00 / 35.00	%Volume	35.00	%Volume	35.10	35.10	0.29%	Pass

Group # 3
Group Name Oxygen
Stated Accy Pct of Reading
Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
20.90 / 20.90	%Volume	20.90	%Volume	21.00	21.00	0.48%	Pass

Group # 4
Group Name Carbon Monoxide
Stated Accy Pct of Reading
Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
1000.00 / 1000.00	PPM	1000.00	PPM	1,003.00	1,003.00	0.30%	Pass

Group # 5
Group Name Hydrogen Sulfide
Stated Accy Pct of Reading
Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
25.00 / 25.00	PPM	25.00	PPM	25.00	25.00	0.00%	Pass

Pine Environmental Services, LLC., Windsor Industrial Park, 92 North Main Street, Bldg 20, Windsor, NJ 08561, 800-301-9663
www.pine-environmental.com

Figure D.4 Calibration Record for GEM 2000+ Gas Characterization Meter – 12DEC2013

INSTRUMENT CALIBRATION REPORT

Pine Environmental Services, LLC.

92 North Main St, Building 20
Windsor, NJ 08561
Toll-free: (800) 301-9663

Pine Environmental Services, Inc.

Instrument ID 16862
Description Gem 2000+
Calibrated 12/12/2013 9:24:25AM

Test Instruments Used During the Calibration (As Of Cal Entry Date)

Test Standard ID	Description	Manufacturer	Model Number	Serial Number / Lot Number	Last Cal Date/ Opened Date	Next Cal Date / Expiration Date
NJ 4 GAS H2S25 CO50 LEL50	4 gas 1266838	Calgaz	4gas	1266838		2/1/2016
NJ 50%CH4/35%CO2 - 13-4639	NJ 50 CH4/35 CO2 34 Liters	American Gas Group	GP12116	13-4639		9/5/2014
NJ CO 1000 - LTH163-RR-CM	CARBON MONOXIDE 1000 PPM	Liquid Technology	GP10730	LTH163-RR-CM		8/1/2016

Notes about this calibration

Calibration Result Calibration Successful
Who Calibrated Juan Hernandez

All instruments are calibrated by Pine Environmental Services, LLC. according to the manufacturer's specifications, but it is the customer's responsibility to calibrate and maintain this unit in accordance with the manufacturer's specifications and/or the customer's own specific needs.

Notify Pine Environmental Services, LLC. of any defect within 24 hours of receipt of equipment
Please call 866-960-7463 for Technical Assistance

Pine Environmental Services, LLC., Windsor Industrial Park, 92 North Main Street, Bldg 20, Windsor, NJ 08561, 800-301-9663
www.pine-environmental.com

Figure D.5 Calibration Record for GEM 2000+ Gas Characterization Meter – 12DEC2013 (continued)

INSTRUMENT CALIBRATION REPORT

Pine Environmental Services, Inc.

92 North Main St, Building 20
Windsor, NJ 08561
Toll-free: (800) 301-9663

Pine Environmental Services, Inc.

Instrument ID 8843
Description Gem 2000+
Calibrated 1/23/2014 10:19:55AM

Manufacturer CES Landtec
Model Number GEM2000+
Serial Number/ Lot Number GM08628
Location New Jersey
Department

State Certified
Status Pass
Temp °C 20.6
Humidity % 21

Calibration Specifications

Group # 1
Group Name Methane
Stated Accy Pct of Reading
Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
50.00 / 50.00	%Volume	50.00	%Volume	50.70	50.00	0.00%	Pass

Group # 2
Group Name Carbon Dioxide
Stated Accy Pct of Reading
Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
35.00 / 35.00	%Volume	35.00	%Volume	34.20	35.10	0.29%	Pass

Group # 3
Group Name Oxygen
Stated Accy Pct of Reading
Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
20.90 / 20.90	%Volume	20.90	%Volume	20.50	20.90	0.00%	Pass

Group # 4
Group Name Carbon Monoxide
Stated Accy Pct of Reading
Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
50.00 / 50.00	PPM	50.00	PPM	40.00	50.00	0.00%	Pass

Group # 5
Group Name Hydrogen Sulfide
Stated Accy Pct of Reading
Range Acc % 0.0000
Reading Acc % 3.0000
Plus/Minus 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
25.00 / 25.00	PPM	25.00	PPM	26.00	25.00	0.00%	Pass

Pine Environmental Services, Inc., Windsor Industrial Park, 92 North Main Street, Bldg 20, Windsor, NJ 08561, 800-301-9663
www.pine-environmental.com

Figure D.6 Calibration Record for GEM 2000+ Gas Characterization Meter – 23JAN2014

INSTRUMENT CALIBRATION REPORT

Pine Environmental Services, Inc.

92 North Main St, Building 20
Windsor, NJ 08561
Toll-free: (800) 301-9663

Pine Environmental Services, Inc.

Instrument ID 8843
Description Gem 2000+
Calibrated 1/23/2014 10:19:55AM

Test Instruments Used During the Calibration **(As Of Cal Entry Date)**

Test Standard ID	Description	Manufacturer	Model Number	Serial Number / Lot Number	Last Cal Date/ Opened Date	Next Cal Date / Expiration Date
NJ 4 GAS - CAN-412-13	4 GAS-H2S/CO/O2/CH4 34 Liters	Airgas	GP 12089	CAN-412-13		5/23/2014
NJ 50%CH4/35%CO2 - 13-4639	NJ 50 CH4/35 CO2 34 Liters	American Gas Group	GP12116	13-4639		9/5/2014

Notes about this calibration

Calibration Result Calibration Successful
Who Calibrated Daniel Teller

All instruments are calibrated by Pine Environmental Services, Inc. according to the manufacturer's specifications, but it is the customer's responsibility to calibrate and maintain this unit in accordance with the manufacturer's specifications and/or the customer's own specific needs.

Notify Pine Environmental Services, Inc. of any defect within 24 hours of receipt of equipment
Please call 866-960-7463 for Technical Assistance

Pine Environmental Services, Inc., Windsor Industrial Park, 92 North Main Street, Bldg 20, Windsor, NJ 08561, 800-301-9663
www.pine-environmental.com

Figure D.7 Calibration Record for GEM 2000+ Gas Characterization Meter – 23JAN2014 (continued)

INSTRUMENT CALIBRATION REPORT

Pine Environmental Services, LLC.
92 North Main St, Building 20
Windsor, NJ 08561
Toll-free: (800) 301-9663

Pine Environmental Services, Inc.

Instrument ID R11082
Description Gem 2000+
Calibrated 7/31/2014 12:48:41PM

Manufacturer CES Landtec
Model Number GEM2000+
Serial Number/ Lot Number GM10393107
Location New Jersey
Department

State Certified
Status Pass
Temp °C 24
Humidity % 44

Calibration Specifications

Group # 1 — **Group Name** Methane — **Stated Accy** Pct of Reading
Range Acc % 0.0000 — **Reading Acc %** 3.0000 — **Plus/Minus** 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
50.00 / 50.00	%Volume	50.00	%Volume	48.70	50.00	0.00%	Pass

Group # 2 — **Group Name** Carbon Dioxide — **Stated Accy** Pct of Reading
Range Acc % 0.0000 — **Reading Acc %** 3.0000 — **Plus/Minus** 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
35.00 / 35.00	%Volume	35.00	%Volume	34.80	35.00	0.00%	Pass

Group # 3 — **Group Name** Oxygen — **Stated Accy** Pct of Reading
Range Acc % 0.0000 — **Reading Acc %** 3.0000 — **Plus/Minus** 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
20.90 / 20.90	%Volume	20.90	%Volume	20.00	20.90	0.00%	Pass

Group # 4 — **Group Name** Carbon Monoxide — **Stated Accy** Pct of Reading
Range Acc % 0.0000 — **Reading Acc %** 3.0000 — **Plus/Minus** 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
50.00 / 50.00	PPM	50.00	PPM	47.00	50.00	0.00%	Pass

Group # 5 — **Group Name** Hydrogen Sulfide — **Stated Accy** Pct of Reading
Range Acc % 0.0000 — **Reading Acc %** 3.0000 — **Plus/Minus** 0.00

Nom In Val / In Val	In Type	Out Val	Out Type	Fnd As	Lft As	Dev%	Pass/Fail
25.00 / 25.00	PPM	25.00	PPM	21.00	25.00	0.00%	Pass

Pine Environmental Services, LLC., Windsor Industrial Park, 92 North Main Street, Bldg 20, Windsor, NJ 08561, 800-301-9663
www.pine-environmental.com

Figure D.8 Calibration Record for GEM 2000+ Gas Characterization Meter – 31JUL2014

HUMBOLDT

HUMBOLDT
3801 N 25th Ave.
Schiller Park, IL 60176

Factory Certificate of Calibration

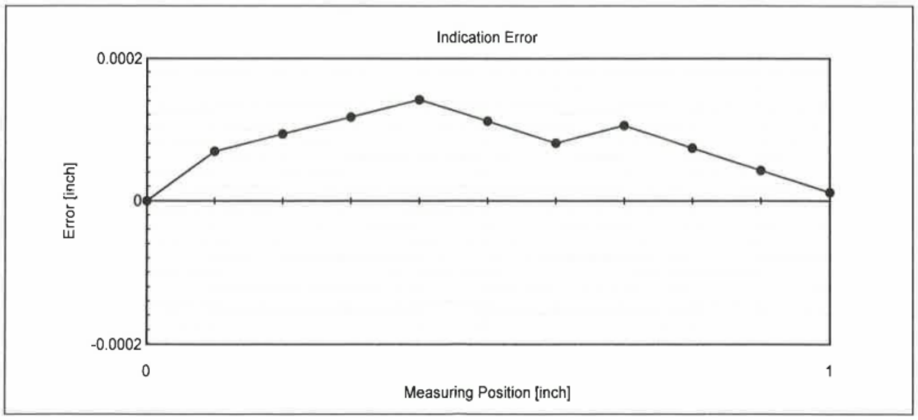
Product Name	LOGIC BASIC
Model No.	BG2110-0-16
Serial No.	110257985
Certificate No.	28769

N.I.S.T. No. 821/268795-03

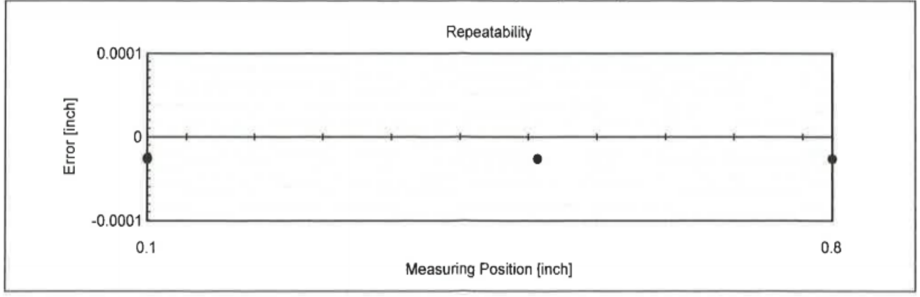
Name of Inspection Standard	CDI Standard
Unit	inch
Scale Interval	0.0001 inch
Measuring Range	1 inch
Reference Point	0 inch
End Point	1 inch

Inspection Item Name	Result	Permissible Value	Judgment
Indication Error	0.000142 inch	0.0002 inch	GO
Hysteresis	----------	----------	N/A
Repeatability	0.0000012 inch	0.0001 inch	GO
Max. Measuring Force	----------	----------	N/A

Inspection Item Name	Judgment
Inspection of Function and Appearance	GO



Indication Error is the sum of accuracy and quantizing error.



Repeatability is taken at three positions, with five readings at each position.

Phone: 800-544-7220
Fax: 708-456-0137
Website: www.humboldtmfg.com

Signature:

Figure D.9 Calibration Record for Digital Dial Gauge Indicator 1

HUMBOLDT

HUMBOLDT
3801 N 25th Ave.
Schiller Park, IL 60176

Factory Certificate of Calibration

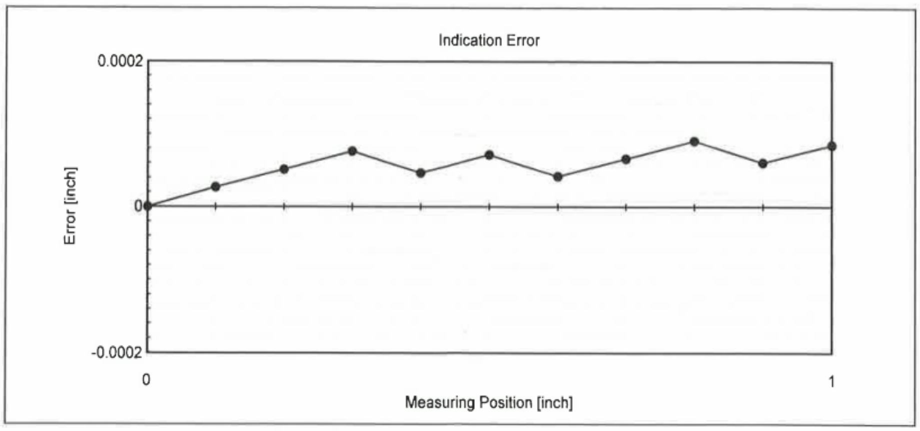
Product Name	LOGIC BASIC
Model No.	BG2110-0-16
Serial No.	110429345
Certificate No.	28935

N.I.S.T. No. 821/268795-03

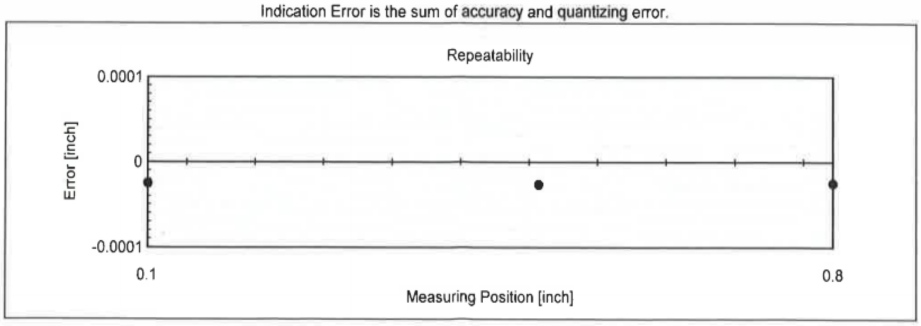
Name of Inspection Standard	CDI Standard
Unit	inch
Scale Interval	0.0001 inch
Measuring Range	1 inch
Reference Point	0 inch
End Point	1 inch

Inspection Item Name	Result	Permissible Value	Judgment
Indication Error	0.0000905 inch	0.0002 inch	GO
Hysteresis	----------	----------	N/A
Repeatability	0.000002 inch	0.0001 inch	GO
Max. Measuring Force	----------	----------	N/A

Inspection Item Name	Judgment
Inspection of Function and Appearance	GO



Indication Error is the sum of accuracy and quantizing error.



Repeatability is taken at three positions, with five readings at each position.

Phone: 800-544-7220
Fax: 708-456-0137
Website: www.humboldtmfg.com

Signature: [signature]

Figure D.10 Calibration Record for Digital Dial Gauge Indicator 2

HUMBOLDT

HUMBOLDT
3801 N 25th Ave.
Schiller Park, IL 60176

Factory Certificate of Calibration

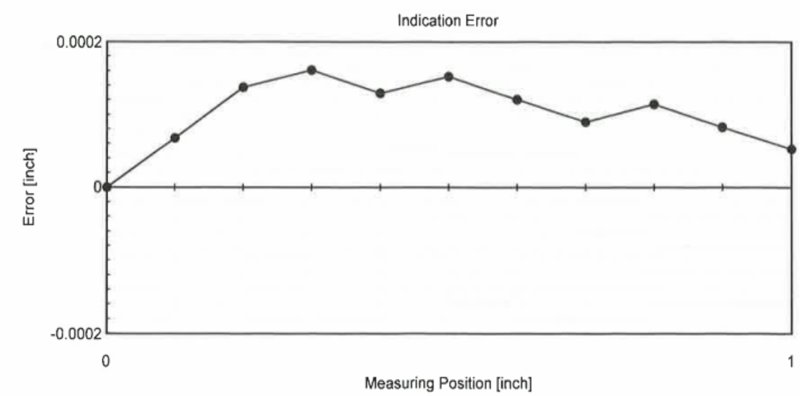
Product Name	LOGIC BASIC
Model No.	BG2110-0-16
Serial No.	110257981
Certificate No.	28765

Name of Inspection Standard	CDI Standard
Unit	inch
Scale Interval	0.0001 inch
Measuring Range	1 inch
Reference Point	0 inch
End Point	1 inch

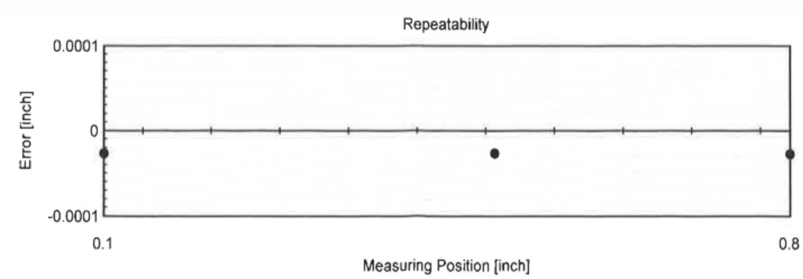
N.I.S.T. No. 821/268795-03

Inspection Item Name	Result	Permissible Value	Judgment
Indication Error	0.0001603 inch	0.0002 inch	GO
Hysteresis	-------	----------	N/A
Repeatability	0.0000016 inch	0.0001 inch	GO
Max. Measuring Force	----------	----------	N/A

Inspection Item Name	Judgment
Inspection of Function and Appearance	GO



Indication Error is the sum of accuracy and quantizing error.



Repeatability is taken at three positions, with five readings at each position.

Phone: 800-544-7220
Fax: 708-456-0137
Website: www.humboldtmfg.com

Signature: [signature]

Figure D.11 Calibration Record for Digital Dial Gauge Indicator 3

HUMBOLDT

HUMBOLDT
3801 N 25th Ave.
Schiller Park, IL 60176

Factory Certificate of Calibration

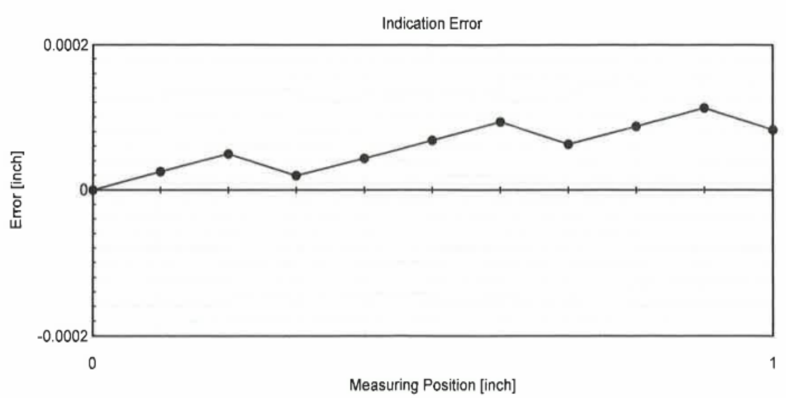
Product Name	LOGIC BASIC
Model No.	BG2110-0-16
Serial No.	110429351
Certificate No.	28941

N.I.S.T. No. 821/268795-03

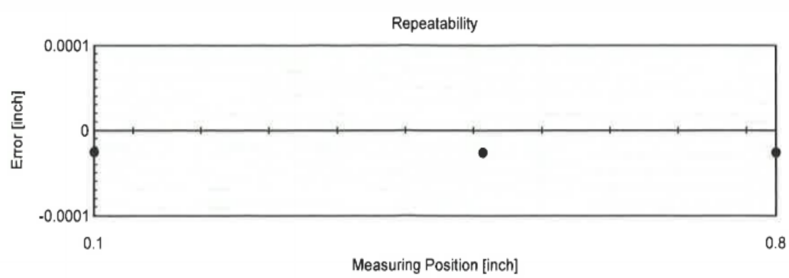
Name of Inspection Standard	CDI Standard
Unit	inch
Scale Interval	0.0001 inch
Measuring Range	1 inch
Reference Point	0 inch
End Point	1 inch

Inspection Item Name	Result	Permissible Value	Judgment
Indication Error	0.0001123 inch	0.0002 inch	GO
Hysteresis	----------	----------	N/A
Repeatability	0.0000012 inch	0.0001 inch	GO
Max. Measuring Force	----------	----------	N/A

Inspection Item Name	Judgment
Inspection of Function and Appearance	GO



Indication Error is the sum of accuracy and quantizing error.



Repeatability is taken at three positions, with five readings at each position.

Phone: 800-544-7220
Fax: 708-456-0137
Website: www.humboldtmfg.com

Signature: ____________

Figure D.12 Calibration Record for Digital Dial Gauge Indicator 4

HUMBOLDT
3801 N 25th Ave.
Schiller Park, IL 60176

Factory Certificate of Calibration

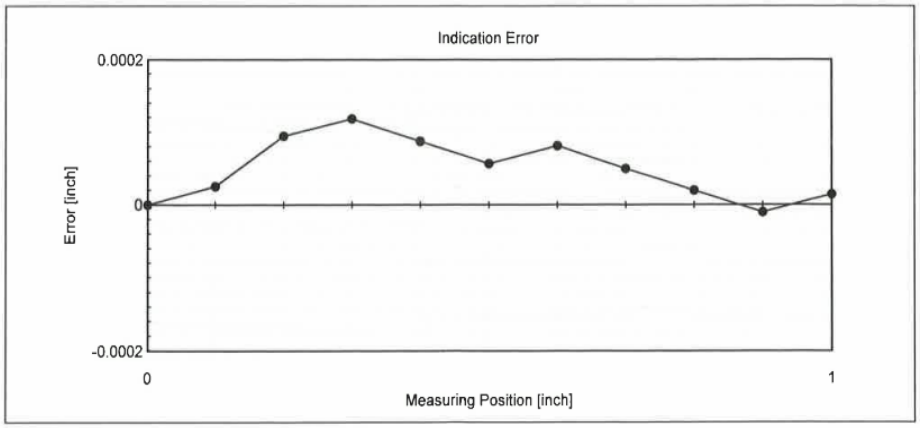
Product Name	LOGIC BASIC
Model No.	BG2110-0-16
Serial No.	110429354
Certificate No.	28944

N.I.S.T. No. 821/268795-03

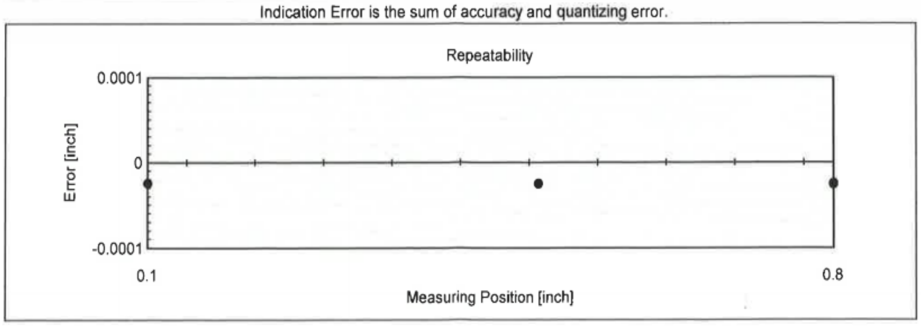
Name of Inspection Standard	CDI Standard
Unit	inch
Scale Interval	0.0001 inch
Measuring Range	1 inch
Reference Point	0 inch
End Point	1 inch

Inspection Item Name	Result	Permissible Value	Judgment
Indication Error	0.0001289 inch	0.0002 inch	GO
Hysteresis	———	———	N/A
Repeatability	0.0000012 inch	0.0001 inch	GO
Max. Measuring Force	———	———	N/A

Inspection Item Name	Judgment
Inspection of Function and Appearance	GO



Indication Error is the sum of accuracy and quantizing error.



Repeatability is taken at three positions, with five readings at each position.

Phone: 800-544-7220
Fax: 708-456-0137
Website: www.humboldtmfg.com

Signature:

Figure D.13 Calibration Record for Digital Dial Gauge Indicator 5

HUMBOLDT

HUMBOLDT
3801 N 25th Ave.
Schiller Park, IL 60176

Factory Certificate of Calibration

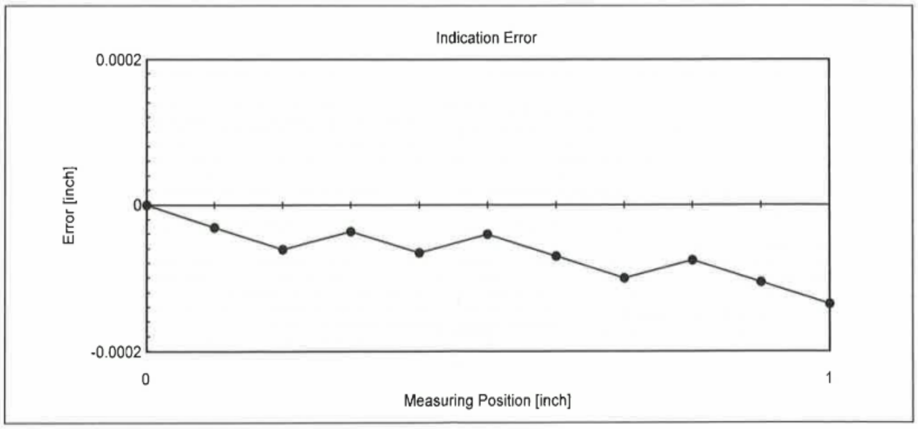
Product Name	LOGIC BASIC
Model No.	BG2110-0-16
Serial No.	110429349
Certificate No.	28939

N.I.S.T. No. 821/268795-03

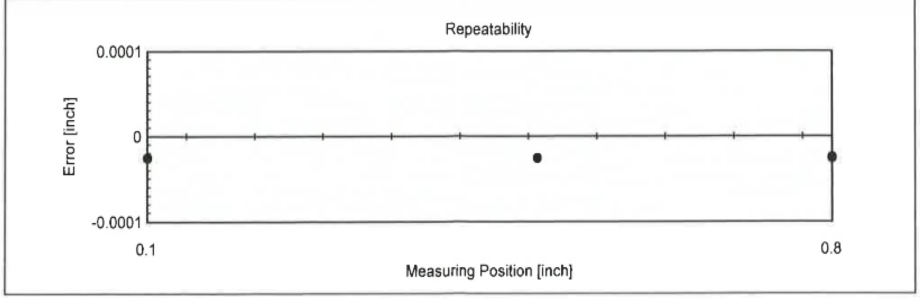
Name of Inspection Standard	CDI Standard
Unit	inch
Scale Interval	0.0001 inch
Measuring Range	1 inch
Reference Point	0 inch
End Point	1 inch

Inspection Item Name	Result	Permissible Value	Judgment
Indication Error	0.0001363 inch	0.0002 inch	GO
Hysteresis	----------	----------	N/A
Repeatability	0.0000016 inch	0.0001 inch	GO
Max. Measuring Force	----------	----------	N/A

Inspection Item Name	Judgment
Inspection of Function and Appearance	GO



Indication Error is the sum of accuracy and quantizing error.



Repeatability is taken at three positions, with five readings at each position.

Phone: 800-544-7220
Fax: 708-456-0137
Website: www.humboldtmfg.com

Signature: ______________

Figure D.14 Calibration Record for Digital Dial Gauge Indicator 6

HUMBOLDT
3801 N 25th Ave.
Schiller Park, IL 60176

Factory Certificate of Calibration

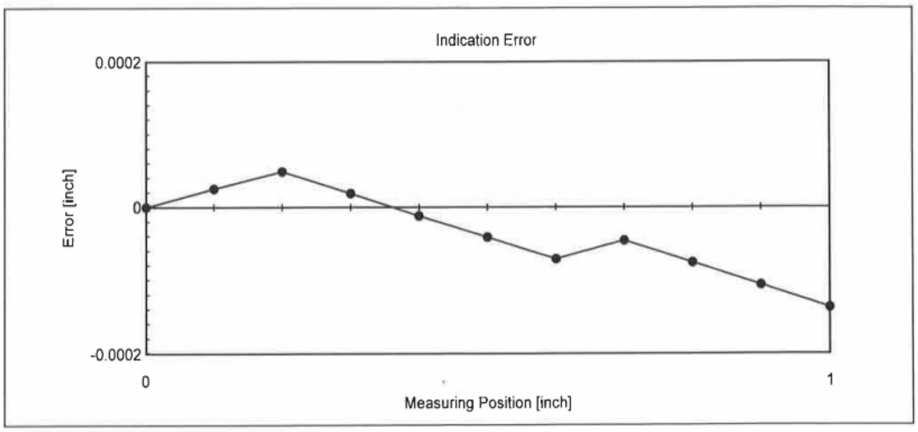
Product Name	LOGIC BASIC
Model No.	BG2110-0-16
Serial No.	110429350
Certificate No.	28940

N.I.S.T. No. 821/268795-03

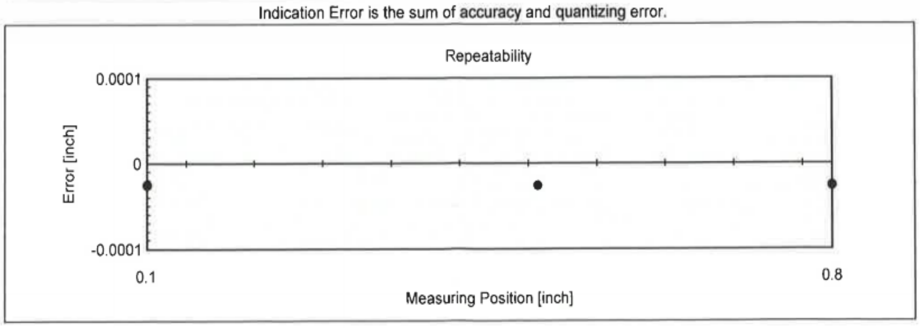
Name of Inspection Standard	CDI Standard
Unit	inch
Scale Interval	0.0001 inch
Measuring Range	1 inch
Reference Point	0 inch
End Point	1 inch

Inspection Item Name	Result	Permissible Value	Judgment
Indication Error	0.0001863 inch	0.0002 inch	GO
Hysteresis	----------	----------	N/A
Repeatability	0.0000012 inch	0.0001 inch	GO
Max. Measuring Force	----------	----------	N/A

Inspection Item Name	Judgment
Inspection of Function and Appearance	GO



Indication Error is the sum of accuracy and quantizing error.



Repeatability is taken at three positions, with five readings at each position.

Phone: 800-544-7220
Fax: 708-456-0137
Website: www.humboldtmfg.com

Signature: ____________

Figure D.15 Calibration Record for Digital Dial Gauge Indicator 7

HUMBOLDT

HUMBOLDT
3801 N 25th Ave.
Schiller Park, IL 60176

Factory Certificate of Calibration

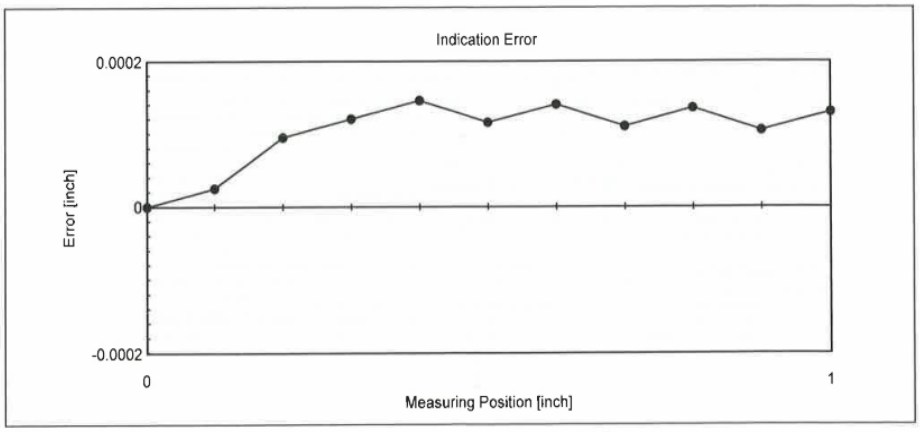
Product Name	LOGIC BASIC
Model No.	BG2110-0-16
Serial No.	110429348
Certificate No.	28938

N.I.S.T. No. 821/268795-03

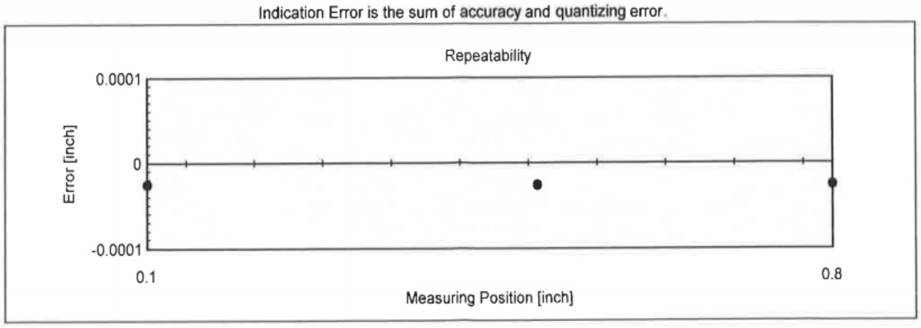
Name of Inspection Standard	CDI Standard
Unit	inch
Scale Interval	0.0001 inch
Measuring Range	1 inch
Reference Point	0 inch
End Point	1 inch

Inspection Item Name	Result	Permissible Value	Judgment
Indication Error	0.0001456 inch	0.0002 inch	GO
Hysteresis	----------	----------	N/A
Repeatability	0.0000012 inch	0.0001 inch	GO
Max. Measuring Force	----------	----------	N/A

Inspection Item Name	Judgment
Inspection of Function and Appearance	GO



Indication Error is the sum of accuracy and quantizing error.



Repeatability is taken at three positions, with five readings at each position.

Phone: 800-544-7220
Fax: 708-456-0137
Website: www.humboldtmfg.com

Signature: ____________

Figure D.16 Calibration Record for Digital Dial Gauge Indicator 8

APPENDIX E

STANDARD FORMS AND PARTS LIST TO REPRODUCE TEST

The author created example instructions and forms to provide repeatability of the method used for this work and future works. Example instructions and forms used by author to guide establishment of bioreactors are included under E.1 – Work Plan and E.2 – Standard Forms Used for Commissioning Bioreactors and Test Equipment. Recognizing the sensitivity of the microorganisms controlling the biodegradation process, it was imperative that the required temperature was maintained, and continuous records for gas production and compression testing also be maintained. The author created an Emergency Workplan which was employed during the experiment and included as E.3 – Emergency Workplan. A list of parts to construct the test set up and bioreactors has also been included as E.4 – Parts List.

E.1 Work Plan and Testing Instructions

WORK PLAN FOR RESEARCH

Authored by: Vatsal A. Shah, P.E. – New Jersey Institute of Technology - Vatsal.Shah.PE@gmail.com

The intent of this work plan is to outline the steps and record keeping intervals of this work

1. Vacuum test bioreactor jars, fittings, lines prior to filling waste
2. Gather material constituents:
   a. Paper
   b. Yard Waste
   c. Wood chippings
   d. Metal
   e. Plastic
   f. Textiles
   g. Glass
   h. Food
   i. Soil
3. Composite samples – Number and Compositions → **FORM A** *(Sample Preparation Record)*
   a. Composite Bioreactor #1 – 18 Composite Samples
   b. Readily Degradable material – 6 samples
   c. Moderately degradable material – 6 samples
   d. Slowly degradable material – 6 samples

Sample weight [lb] =		2.10	**Weight required [lb]**			
Type	**Constituent**	**Percentage**	**Composite**	**Readily**	**Moderately**	**Slowly**
M	Paper	38%	0.798		1.86	
R	Yard waste	6%	0.126	0.504		
M	Wood chippings	2%	0.042		0.10	
S	Plastic	13%	0.273			2.1
M	Textiles	3%	0.063		0.15	
N	Glass	11%	0.231			
R	Food	19%	0.399	1.596		
N	Soil	8%	0.168			
	Sum=	100%	2.10	2.10	2.10	2.10

EXAMPLE COMPOSITION

Note- prepared slightly more than 2.0 lbs so moisture content check can be performed prior to conditioning

4. Mix all samples in large zip lock bag. Take small portion (~0.1 lb) to determine initial moisture content
5. Moisture condition samples to approximately 170 percent of weight → **Form B** (*Moisture Conditioning Record)* Add additional weight of water as necessary to reach moisture required
6. Prepare water bath to 110 deg.F temperature → **Form C** *(Water Bath Temperature Log)*

Revision: 15APR2012

Page 1 of 3

Figure E.1.1 Standard Work Plan for Research (Page 1 of 3)

WORK PLAN FOR RESEARCH

Authored by: Vatsal A. Shah, P.E. – New Jersey Institute of Technology - Vatsal.Shah.PE@gmail.com

7. Connect leachate recirculation piping, gas collection piping, condensate return piping, flow meter, and tedlar gas bags
8. Submerge bioreactors in water bath
9. Introduce leachate throughout test period to increase moisture content to 40 to 45% → **Form D** *(Leachate recirculation record)*
10. Remove samples for consolidation testing at bi-monthly intervals. → **Form E** *(Consolidation Record)*
    - i. Disconnect bioreactor from gas collection and leachate recirculation system
    - ii. Remove up to sample from bioreactor and place in 1 gallon zip-lock bag
        1. ¼ sample used for consolidation testing
        2. ¼ sample used for moisture content testing
        3. ¼ sample used to be send for C+H/L testing
        4. ¼ sample retained to be frozen as contingency
    - a. Consolidation Test Procedures:
        - iii. Rotate/shake zip lock bag to ensure proper mixing and uniform moisture content
        - iv. Remove approximate amount of sample for consol testing and begin to place sample to form ¼" thick (loose) lifts inside the ring [approximately one tablespoon per lift].
        - v. Place a 2.4" diameter hard rubber stopper on top of lift, and drop a 3.5 lb cylindrical weight from ~1" height 7 times to tamp sample
        - vi. Continue procedure until a 1" thick compacted sample is created (approx. 6 – 7 loose lifts) - Some cosmetic patching may be required
        - vii. Perform consolidation test and record dial gauge readings using **Form E**

11. C+H/L Testing: **Completed bi-weekly for first 3 months, then monthly thereafter**. Should also be taken prior to the start of a consolidation test. → **Form F** – *(C+H/L Testing Record)*
    - a. Record following information:
        - i. Amount of waste removed from bioreactor (so gas flow record per unit weight of waste can be accurately maintained)
        - ii. Date removed from bioreactor
        - iii. Total amount of sample removed (moist)
        - iv. Moisture Content
        - v. Dry Weight (obtain from lab testing)
        - vi. Total weight and date sent for testing
        - vii. Date received, date processed, date tested
        - viii. C+H/L result

12. Leachate recirculation: **Completed weekly** to keep sample moisture content between 40 and 45%

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Figure E.1.2 Standard Work Plan for Research (Page 2 of 3)

WORK PLAN FOR RESEARCH

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   a. Moisture content determined at times when samples are removed for C+H/L testing or consolidation testing. If moisture content drops below 40%, additional leachate should be added to bring up to 40%.
   b. **Check moisture content probe on a weekly basis**

13. Gas Flow Meter: **Daily Readings → Form G** *(Gas Flow Record)*
    a. Gas flow rate should be plotted at daily intervals to determine prescriptive "shape" of gas generation curve.
    b. Check volume by fill rate of tedlar bag and integrating under curve under time t_0 (beginning of gas bag) and t_1 (time gas bag is filled)

14. Tedlar gas bags: **Change as needed**
    a. As bags begin to fill to their capacity, close valve from gas flow meter, remove bag, check composition, and empty bag for re-use.
    b. Verify volume collected by integrating flowrate of past days since last removal of bag. If deviation greater than 5% is noticed, check gas flow meter for any errors

15. Gas composition: **As needed → Form H** *(Gas Composition Record)*
    a. Use Landtec GEM 2000+ meter. Record pressure from in-line pressure gauge

16. Water bath temperature: **Daily AM/PM → Form C**
    a. Use submerged temperature data logger. Water bath should remain ± 110 deg. F. Adjust heating element as necessary to achieve correct temp.
    b. Manual readings as often as possible

17. Water level in bath should be constant. Check control mark on tank and record +/- water level [inches from control mark] **Check weekly**

18. Waste mass balance: Whenever sample is removed from bioreactor → **Form I** *(Bioreactor Mass Balance Record)*
    a. Accurate record of waste remaining in bioreactor should be kept so gas/lb of waste can be accurately recorded

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Figure E.1.3 Standard Work Plan for Research (Page 3 of 3)

E.2 Standard Forms Used for Commissioning Bioreactors and Test Equipment

FORM A Date:

Sample Preparation

Sample Jar/Bag No.	Paper	Yard Waste	Wood Chippings	Plastic	Textiles	Glass	Food	Metal	Soil	Total
IDEAL	**0.8**	**0.13**	**0.04**	**0.26**	**0.06**	**0.23**	**0.4**	**0.01**	**0.17**	**2.1**
C-1										
C-2										
C-3										
C-4										
C-5										
C-6										
C-7										
C-8										
C-9										
C-10										
C-11										
C-12										
C-13										
C-14										
C-15										
C-16										
IDEAL	**-**	**0.5**	**-**	**-**	**-**	**-**	**1.6**	**-**	**-**	**2.1**
R-1	-									
R-2	-									
R-3	-									
R-4	-									
R-5	-									
R-6	-									
IDEAL	**1.86**	**-**	**0.1**	**-**	**0.14**	**-**	**-**	**-**	**-**	**2.1**
M-1										
M-2										
M-3										
M-4										
M-5										
M-6										
IDEAL	**-**	**-**	**-**	**1.3**	**-**	**-**	**-**	**-**	**0.6**	**2.1**
S-1	-	-	-							
S-2	-	-	-							
S-3	-	-	-							
S-4	-	-	-							
S-5	-	-	-							
S-6	-	-	-							

Note: "C" denotes Composite sample, "R" denotes Readily Degradable, "M" denotes Moderately Degradable, "S" denotes Slowly Degradable sample

Figure E.2.1 Standard Form A – Sample Preparation

FORM B

Moisture Conditioning Record

Date:

Sample Jar/Bag No.	Weight of Bag [lbs]	Weight of Bag [lb]	Initial Moisture Content [%]	Dry Weight [lb]	Amount of Water to Add (Dry Weight x 1.7) [lb]	Weight of Sample @ 170% M.C.	Weight of Sample + Bag @ 170% M.C.
C-1							
C-2							
C-3							
C-4							
C-5							
C-6							
C-7							
C-8							
C-9							
C-10							
C-11							
C-12							
C-13							
C-14							
C-15							
C-16							
R-1							
R-2							
R-3							
R-4							
R-5							
R-6							
M-1							
M-2							
M-3							
M-4							
M-5							
M-6							
S-1							
S-2							
S-3							
S-4							
S-5							
S-6							

Note: "C" denotes Composite sample, "R" denotes Readily Degradable, "M" denotes Moderately Degradable, "S" denotes Slowly Degradable samples

Figure E.2.2 Standard Form B – Moisture Conditioning Record

FORM C

Manual Water Bath Temperature Log

BIOREACTOR Tub.:

Date	A.M. [˚F]	P.M. [˚F]	Pump recirculating?	Water level in bath (+/- control mark [inch])	Amount of Water Added [Gal]	Notes

Figure E.2.3 Standard Form C – Manual Water Bath Temperature Log

FORM D

Leachate Recirculaton Record

Date	Samples Charged	Initial Moisture Content [%]	Weight of Waste in Bioreactors [lb]	Amount of Leachate Added to bring to 45% M.C. [mL]	Interval Since Last Charge [Day]	Cum. Days Between Changes

Figure E.2.4 Standard Form D – Leachate Recirculation Record

FORM E
Consolidation Record

SAMPLE No.
Load [tsf]
Date Applied:

Time	Elapsed Time [min:sec]	$\sqrt{t}$ [min$^{1/2}$]	Dial Gauge Reading [in]
	0		
	0.1		
	0.25		
	0.5		
	1		
	2		
	4		
	8		
	15		
	30		
	60		
	120		
	240		
	480		

Figure E.2.5 Standard Form E – Consolidation Record

FORM F
(C+H)/L Testing Record

Sample Number	Date Removed	Removed From Bioreactor Number	Total Amount of Sample Removed [lb]	Sample Sent to Barlaz [lb]	Sample Used for M.C. [lb]	Moisture Content [%]	Waste Removed from Bioreactor, Dry [lb]	Date Sent to Barlaz	Tracking No.	Date Received	Date Processed	Date Tested	C+H/L Result

Figure E.2.6 Standard Form E – (C+H)/L Testing Record

FORM G

Gas Flow Record

Date of Reading	Gas Flow Meter [C, R, M, S]	Cumulative Days Snice Start	Gas Flow Reading [sccm]	Dry Weight of Waste in Bioreactors [lb]	Gas Flow Rate per Waste [sccm/lb]	Theoretical Gas Remaining [ft^3/lb]

Figure E.2.7 Standard Form G – Gas Flow Record

FORM H

Gas Composition Record

Date of Reading	Bioreactor [C, R, M, S]	Gas Flow Reading [sccm]	Approx Tedlar Bag Volume [L]	% CH4	% CO2	CO [ppm]	% O2	H2S [ppm]	Gas Flow Pressure [psi]

Figure E.2.8 Standard Form H – Gas Composition Record

FORM I

Bioreactor Mass Balance Record

Sample	Removed Date	Weight Material Removed [lb]	Weight Used for Consol Testing [lb]	Weight Sent to Barlaz [lb]	Weight Used for M.C. [lb]	Moisture Content [%]	Dry Weight of Waste Removed [lb]

Figure E.2.9 Standard Form I – Bioreactor Mass Balance Record

Daily Inspection Checklist

IN THE EVENT OF A POWER OUTAGE OR EMERGENCY
CONTACT ________ AT ______________ (phone) AND _____________ (e-mail) IMMEDIATELY

DATE:____

REVIEWER NAME:____

I. Daily

a. AM:

- ☐ **Fill out gas flow record (see 3 hanging clipboards on cart between tubs - Form G")**
  - ☐ "Composite" meter (#1) - DATE, & TIME OF READING
  - ☐ "Readily" meter (#2) - DATE, & TIME OF READING
  - ☐ "Moderately" meter (#3) - DATE, & TIME OF READING
- ☐ **Check thermometers and record reading (see Clipboard attached to tub - "Form C")**
- ☐ **Check water level in consolidation rings; fill if necessary**

b. PM:

- ☐ **Fill out gas flow record (see 3 hanging clipboards on cart between tubs – "Form G")**
  - ☐ "Composite" meter (#1) - DATE, & TIME OF READING
  - ☐ "Readily" meter (#2) - DATE, & TIME OF READING
  - ☐ "Moderately" meter (#3) - DATE, & TIME OF READING
- ☐ **Check Humboldt data logger; ensure not reset (reset if all readings 0.00)**
- ☐ **PC power supply and backup battery**
- ☐ **Check tedlar bags to ensure not overinflated**

c. Housekeeping

- ☐ Check water tubs/area around tubs for water or leaks
- ☐ Check heaters to ensure they are on (red light) and set to "10"
- ☐ Check gas bags (plastic bags on cart racks) to ensure they are not deformed/swollen

II. Weekly (every Sunday)

- ☐ **Send samples to Barlaz/check (C+H)/L test results**
- ☐ **Perform in-situ moisture content moisture reading**
- ☐ **Add leachate as required (bring up to 45% M.C.)**
- ☐ **Check consolidation test results/perform consolidation test**

NOTES:____

____

____

Figure E.2.10 Sample Daily Inspection Checklist

E.3 Emergency Workplan

Emergency Workplan

IN THE EVENT OF A POWER OUTAGE OR EMERGENCY, CONTACT _______ AT _____________ (phone) AND _____________ (e-mail) IMMEDIATELY

I. Objective

This workplan has been created to serve as a guide in the event of an emergency to allow uninterrupted data collection and prevent any losses or gaps in data which may compromise the research experiment.

II. Summary

It is the goal of this research work to understand the settlement behavior of landfill waste and the rate at which gas is produced by the waste material. To test this, waste was created and mixed together and put into 2 gallon jars and submerged in a water bath. This arrangement of the jars is called the bioreactor.

Two bioreactors are included in this work:

- Bioreactor 1 – contains 24 sample jars (called "composite sample")
- Bioreactor 2 – contains 18 sample jars (called "individual samples")
  - 6 jars labeled Readily ("R")
  - 6 jars labeled Moderately ("M")
  - 6 jars labeled Slowly ("S")

At certain times, samples will be removed from the bioreactor so that they can be tested for their settlement behavior. Samples undergoing settlement testing will be in one of the 8 table-top consolidation apparatuses. Each consolidation apparatus has a digital dial gauge indicator on it showing the settlement caused by the load, and these gauges are connected to one of two data reader and computer. The data reader is the central control unit and stores the data.

Gas will also be measured from the samples using a digital gas flow meter. Four gas meters are installed, one for each sample type (the composite and 3 individual samples). This flow rate is read daily, at minimum.

A schematic of this arrangement is provided as **Attachment 1**

III. Emergency Items

The following items MUST be tended to in the event of an emergency:

Within 30 minutes of power outage – Connect RED marked extension cords

1. Consolidation data loggers (two) - connect to gas-powered generator
2. Gas flow meter – Connect extension cord connecting all 4 to generator

Within 4 hour of power outage – Connect YELLOW marked extension cords

1. Water bath thermostat (two) – connect extension cord to separate generator (do not use same as consolidation and flow meter as it may overload one generator)

Within 8 hour of power outage – Connect GREEN marked extension cords

1. Data acquisition computer

Figure E.3.1 Emergency Workplan

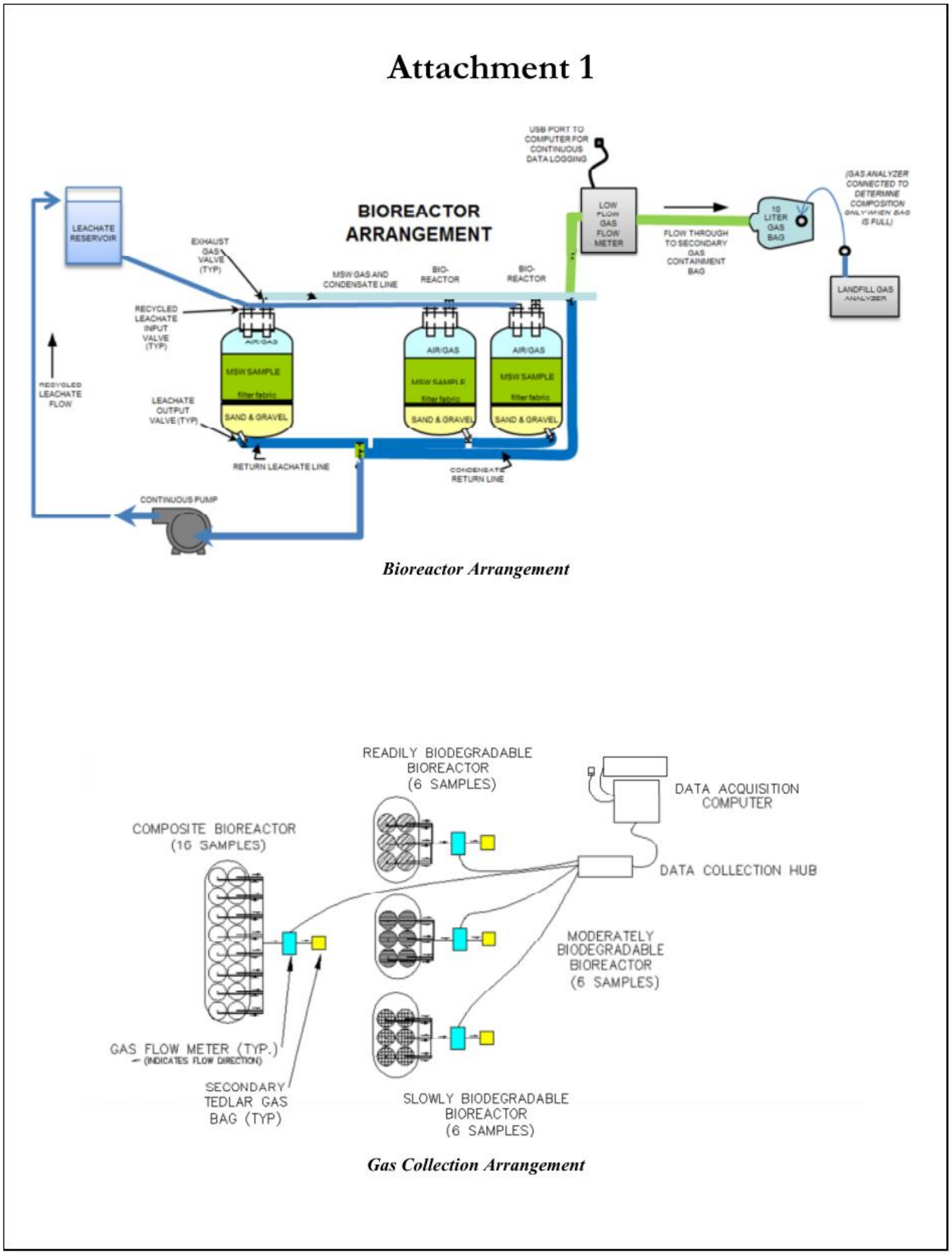

Figure E.2.2 Attachment 1 to Emergency Workplan

E.4 Parts List

Table E.4.1 Parts List

Item	Vendor	Part No	# Used	Use
Reactor ports	Cole-Parmer	EW-06259-10	34	Fitting to connect to gas and leachate ports
Gas bag, 1 L	SKC	231-01	3	Gas collection
Gas bag, 5 L	SKC	231-05	3	Gas collection
Gas bag, 50 L	SKC	231-50	5	Gas collection
Reactor jar	United States Plastic Corp.	71169	34	Sample jars
Gas Bag Valve	Upchurch Scientific	P-721A	4	Gas valve to close off gas bag
Marine Sealant	3M	Auto/Marine Sealant	12	Waterproof seal of leachate ports
Tubing	Cole-Parmer	EW-06408-50	2	Tubing to connect leachate and gas
Leachate bag	VWR Scientific	68000-580 (Baxter 2B8122)	4	Collect leachate
Tubing clamps	Speedy Products	AA	34	Clamp connection for leachate port
Tubing clamps	Speedy Products	B	34	Clamp connection for gas port
Tubing clamps	Speedy Products	BB	34	Clamp connection for recirculation port
Fitting from tubing to gas bag	McMaster-Carr	51465K117	5	Convert gas pipeing 1/4" diam to 5/16" to fit gas bag
Gas bag valve	Upchurch Scientific	P-624	34	Open/Close Gas Valve
Tubing (gas)	Cole-Parmer	EW-06408-50	4	Connect gas bags to totalizer and gas bag
Tubing (leachate)	Cole-Parmer	EW-06408-03	4	Connect leachate to circulation line
Tubing connector	McMaster-Carr	5463K606	34	Connect gas bags to totalizer and gas bag
leachate sampling port	McMaster-Carr	5463K532	34	Connect leachate to circulation line
Gas totalizer	Sierra Instruments	Microtrak 101	3	Methane flow rate measurement
Water heater	Humbolt	H-2986A	2	Heat water bath

Table E.4.2 Parts List (Continued)

Item	Vendor	Part No	# Used	Use
RS232 connection for gas totalizer	Sierra Instruments	RS232	3	Connection to data acquisition hub
Temperature control data logger via USB	Thermoworks	TW-USB-1	2	Water temperature logging
Stock tank	Agway	2x2x2 Round End Stock Tank	2	Water bath
Water recirculation pump	Beckett	80217 - 325 gph pump	2	Continuous circulation of water bath water
Computer	Lenovo	ThinkCentre Edge 72 3484FDU	1	Data logging
Monitor	Samsung	S22B150N	1	Office
UPS Power Supply	CyberPower	LCD Series UPS 1500VA 900W	1	Backup power
USB Extension cords	Mediabridge	Hi-Speed USB 2.0 A-Male to A-Female	10	Extension Cord
Plastic Dip	Plastic Dip	Black	4	Plastic lining of tub for corrosion resistance
Digital Scale	Ohaus	CL2000	1	Scale to measure weights
Consolidation Frame	Humboldt	HM-1000	8	Frame for consolidometer
Floor Mounted Stand for 3 Consolidometers	Humboldt	HM-1100.3	3	Bench for consolidometers
2.5" dia. Fixed Ring Consolidation Cell	Humboldt	HM-1220.25	8	Consolidation ring
16 TSF weight set	Humboldt	HM-1120	8	Calibrated weights for consolidation test
Digital dial gauge indicator, 1" x .0001"	Humboldt	HM-4469.10	8	Dial gauge to measure strain
Cable for Digital Indicator	Humboldt	HM-4469C	8	Cable to connect to data logger

Table E.4.3 Parts List (Continued)

Item	Vendor	Part No	# Used	Use
4-Channel Digital Data Logger	Humboldt	HM-2330D.3F	2	Data logger to capture dial gauge readings
HTMS Consolidation Reporting Software	Humboldt	HM-1100SW	1	Computer software to plot results
USB to RS485 Serial Cable	Humboldt	HM-000379	1	Connect data logger to computer
Ethernet Cable	Humboldt	HM-000376	1	Connect to printer
Filter Paper	Humboldt	HM-4189	1	Filter paper for consolidation test
Gas Composition meter	Landtec	GEM2000+	1	Gas composition
Moisture Sensors	IMKO	PICO64	4	Non-destructive moisture content of sample

APPENDIX F

DERIVATION OF EQUATIONS

Derivations for equations proposed throughout this work are provided herein.

Derivation of Equation 3.2 – Percent CO_2

$$Q_{total} = (Q_{CH4} + Q_{CO2})$$

$$Q_{CH_4} = Q_{total} \times ({P_{CH_4}}/{100})$$

$$Q_{CO_2} = (Q_{total} - Q_{CH_4}) = \frac{Q_{CH_4}}{{P_{CH_4}}/{100}} - Q_{CH_4}$$

$$Q_{CO_2} = Q_{CH_4} \times (\frac{1}{{P_{CH_4}}/{100}} - 1) \qquad (3.2)$$

Derivation of Equation 3.4 - Raghu and Disbrow Gas Production Model – Phase 1

For straight line portion (Phase 1 - 0 to t_1 years), Let V_o = peak of gas production curve

Slope of line = V_o

For any time, t_n, the value of y-ordinate = t_n V_o

Therefore area under curve, $V_{phase1} = ½\ t_n \times (t_nV_o) = V_ot_n^2/2$ (3.4)

Derivation of Equation 3.5 - Raghu and Disbrow Gas Production Model – Phase 2

For decay portion of curve (Phase 2 - 10 to t_2 years):

V_{phase2} = $\int_{t_1}^{t_n} V_1 \times e^{-k(t-t_1)} dt$

Where $V_1 = V_0$ x t_1

Assuming t_1 = 10 years, $V_1 = 10V_o$

As V_1 is a constant, it can be moved in front of integral, so V_{phase2} = $V_1 \int_{t_1}^{t_n} e^{-k(t-t_1)} dt$

Let $u = -k(t-t_1)$

Therefore, V_{phase2} = $V_1 \int_{t_1}^{t_n} e^u dt$

Since t_1 = 10, $u = -k(t\text{-}10) = -kt + 10k$

du= -k dt

dt = -du/k

Substituting, V_{phase2} = $V_1 \int_{t_1}^{t_n} e^u \frac{-du}{k}$

Integrating, V_{phase2} = $\frac{-V_1}{k} e^u + C$

$$V_{phase2} = \frac{-V_1}{k} e^{-k(t-10)} + C \qquad (3.5)$$

Derivation of Equation 3.6 - Raghu and Disbrow Gas Production Model – Total Gas Production

$V_{total} = V_{phase\ 1} + V_{phase\ 2} = \frac{V_o t_n^{\ 2}}{2} + \frac{-V_1}{k} e^{-k(t-10)} + C$

Substituting $V_1 = 10V_o$, $V_{total} = V_o(\frac{t_1^{\ 2}}{2} - \frac{10}{k} e^{-k(t-10)}) + C$ (3.6)

Derivation of Equation 6.7 - Composite Waste Decay Modifier by Weighted Average

$V_{total} = V_r + V_m + V_s$

Where $V_r = V_{o_r} e^{-k_r t}$

and $V_m = V_{o_m} e^{-k_m t}$

and $V_s = V_{o_s} e^{-k_s t}$

Then, $V_{o_r} = n_r V_o$

Likewise $V_{o_m} = n_m V_o$

and $V_{o_s} = n_s V_o$

Therefore, $V_{total} = V_o e^{-k_c t} = n_r V_o e^{-k_r t} + n_m V_o e^{-k_m t} + n_s V_o e^{-k_s t}$

Dropping out V_o, $e^{-k_c t} = n_r e^{-k_r t} + n_{mo} e^{-k_m t} + n_s e^{-k_s t}$

Taking $\log_e$ of entire expression, $k_c = n_r k_r + n_m k_m + n_s k_s$ (6.7)

Derivation of Equation 6.14 – Relationship of Biodegradation Ratio (B), Inert Ratio (R), and Strain (ε_z)

The biodegradation ratio is expressed as $B = \dfrac{\partial H}{H(1-R)}$

Rearranging, $\partial H = BH(1-R)$

Strain is defined as $\varepsilon_z = \dfrac{\partial H}{H}$

Therefore, substituting ε_z, $H\varepsilon_z = \partial H = BH(1-R)$

Rearranging, $\varepsilon_z = B(1-R)$ (6.14)

Derivation of Equation 6.17 - Relationship of Field-Calculated Decay Constant, k, from Settlement Curves

For a unit of waste, initial volume = V_o and volume of waste following degradation = V_f

Strain defined as $\varepsilon_z = \dfrac{V_o - V_f}{V_o}$

Where $V_f = V_o e^{-kt}$

Therefore, $\varepsilon_z = \dfrac{V_o(1-e^{-kt})}{V_o} = 1-e^{-kt}$

Subtracting 1 from both sides, $\varepsilon_z - 1 = -e^{-kt}$

Multiplying by -1 and taking natural log of both sides, $\log_e(1-\varepsilon_z) = \log_e(e^{-kt})$

Simplifying, $\log_e(1-\varepsilon_z) = -kt$

Then, k may be determined as the slope of the line between two values, or:

$$k = \frac{\log_e(1-\varepsilon_{z_1}) - \log_e(1-\varepsilon_{z_2})}{t_2 - t_1} \quad (6.17)$$

Derivation of Equation 7.2 - Percent Biodegradation (%B) Considering Density

By definition, weight = Volume x Unit weight

Subscripts "i" for initial and "f" for final are used in the derivation of the expression.

Therefore, $W_f = \gamma_f V_f$

and $W_i = \gamma_i V_i$

Dividing W_f/W_i, $(W_f/W_i) = (\gamma_f/\gamma_i)(V_f/V_i)$

Rearranging, $(V_f/V_i) = (W_f/W_i)/(\gamma_f/\gamma_i)$

Let $(\gamma_f/\gamma_i) = \eta$

Substituting, $(v_f/v_i) = (W_f/W_i)/\eta$

Assuming that $(v_f/v_i) = (W_f/W_i)$

Percent Biodegradation by volume = 100% * $[(v_f - v_{i)}/v_i]$ = (100% * $[(v_f/v_i)$-1]

And Percent Biodegradation converted, %Bconverted = 100% * $((1/\eta)(W_f/W_i)]$-1)

Substituting η, $$\%B_{converted} = [1 - (\frac{\gamma_i W_f}{\gamma_f W_i})] \times 100\% \qquad (7.2)$$

APPENDIX G

CALCULATIONS TO DETERMINE THEORETICAL GAS PRODUCTION AND END OF EXPERIMENT

G.1 Calculations to Determine Theoretical Gas Production

Calculations for theoretical total gas quantity were conducted using the lambda method of gas production as modified by Lifrieri and detailed in Chapter 3. Calculations are presented as Tables G.1, G.2, and G.3 for composite, readily, and moderately degradable bioreactors, respectively. A theoretical total gas production of 6.23, 9.04, and 8.27 cubic feet per pound waste was determined for composite, readily, and moderately degradable bioreactor sets, respectively. Theoretical total methane gas volumes of 3.43, 4.97, and 4.55 cubic feet per pound waste were predicted based on stoichiometry which predicts methane comprises 55% of the total gas. The values were used to assess the methane remaining, percent total theoretical remaining, and evaluate cumulative production from flow meters as presented in Appendix B.2.

Computations for total theoretical gas production of slowly bioreactors are provided as Table G.4 and indicate a potential of 11.29 cubic feet per pound waste. However, it has been determined by the author and others (Shah et. al 2007, Ishigaki et al. 2003, Tchobanoglous 1993, Albertson et. al, 1987) that the use of models to predict the gas production for plastics (which comprise "slowly" bioreactors used during this work) is inappropriate as models greatly overestimates the theoretical gas production. Detailed discussion is presented in Chapter 3. Durmusoglu et al. (2005) recommend a total theoretical gas potential of 7.83 ft^3/lb for slowly decomposable wastes.

Table G.1 Calculation for Theoretical Maximum Gas Production for Composite Bioreactors by Lambda Method

STEP 1

Step 1: Break out composition into % descriptive modifiers

Inputted				Calculated				
Waste	Type	% MSW	Wet Wt [lb]	V_i	% of Type	Dry weight	W_i [lb]	Total Wt [lb]
Food Yard Waste	R R	19% 6%	19 6	V_r =	25%	9.62 3.04	W_r =	12.65
Wood Paper Textiles	M M M	2% 38% 3%	2 38 3	V_m =	43%	1.01 19.23 1.52	W_m =	21.77
Plastic	S	13%	13	V_s =	13%	6.58	W_s =	6.58
Soil Glass	ND ND	8% 11%		V_n =	19%		W_n =	0.00
Decomposable Moist Wt=			81	V_t =	100%	41.00	Dry Wt	

V_i = Volume of Type of Waste W_i = Weight of Type of Waste (based on 100 lb sample)

Average moisture content of waste, m.c. = 40%

NOTE: moisture content defined as W_{water}/W_{tot}, unlike geotech definition of W_w/W_{dry}

For 100lb wet sample, weight of water = W_{tot} x m.c. = 0.4 * 100lb = 40 lb

Wt of decomposable fraction - all water contained in waste= 81 - 40 lb = 41 lb

STEP 2

Step 2: Determine Lambda Factors   Characteristic equation: $V_{ti} = V_i\ e^{-(\lambda it)}$

λ_r = 0.1386

λ_m = 0.0231

λs = 0.0173

STEP 3

Step 3: Select year of interest to determine modifier, V_i (t=173 years)

For this example, use 173 year for ultimate gas production at end of decomposition

Readily: V_r@173yrs = (25) $e^{-[(0.1386)(173)]}$ = 9.65E-12

Moderately: V_m@173yrs = (43) $e^{-[(0.0231)(173)]}$ = 7.90E-03

Slowly: V_s@173yrs = (13) $e^{-[(0.0173)(173)]}$ = 6.52E-03

STEP 4

Step 4: Determine % decomposed

% decomposed = $(V_i - V_{it})/V_i$

Readily: $\%D_r$ = (0.25-(9.56E-12))/0.25 x 100% = 100%

Moderately: $\%D_m$ = (0.43-(7.90E-03))/0.43 x 100% = 99%

Slowly: $\%D_s$ = (0.13-(6.52E-03))/0.13 x 100% = 95%

STEP 5

Step 5: Determine (dry) weight of decomposed wastes

Weight of decomposed weight = % decomposed x dry weight fraction

Readily: 100% x (12.65 lb) 12.65 lb

Moderately: 99% x (21.77 lb) 21.77 lb

Slowly: 95% x (6.58 lb) 6.46 lb

Total decomposed weight= 40.88 lb

Table G.1 Calculation for Theoretical Maximum Gas Production for Composite Bioreactors by Lambda Method (continued)

STEP 6	**Step 6: Determine gas produced using stoichiometric reaction masses** Reaction Masses from stoichiometry (Calculated in Table 3.1) $C_aH_bO_cN_d$ = 1106.5 CH_4 = 406.8 NH_3 = 17 H_2O = 277.2 CO_2 = 959.8
STEP 7	**Step 7: Determine volume of gas produced up to time, *t*** (30 years for example) Volume methane produced, $V_{CH4} = (M_{CH4})(W_{degraded}) / [(M_{CaHbOcNd})(W_{CH4})$ V_{CH4} = [(406.8)(40.88)] / [(1106.5)(0.0448)] = 335.47 ft^3 V_{CO2} = [(959.8)(40.88)] / [(1106.5)(0.1234)] = 287.35 ft^3 Total gas, $V_{total} = V_{CH4} + V_{CO2}$ = 622.82 ft^3 % CH4 = 54% %CO_2 = 46% Theoretical gas produced per lb waste up to 173 years= V_{total}/sample weight At end of practical biodegradation, theoretical total gas produced = 622.82 Gas production at time t (173 years) = 622.82 ft^3/100lb = **6.23** **ft^3**

Table G.2 Calculation for Theoretical Maximum Gas Production for Readily Degradable Bioreactors by Lambda Method

TEP 1

Step 1: Break out composition into % descriptive modifiers

Inputted				Calculated				
Waste	Type	% MSW	Wet Wt [lb]	V_i	% of Type	Dry weight	W_i [lb]	Wt of Type
Food	R	76%	76	V_r =	100%	45.60	W_r =	60.00
Yard Waste	R	24%	24			14.40		
Wood	M	0%	0	V_m =	0%	0	W_m =	0
Paper	M	0%	0			0		
Textiles	M	0%	0			0		
Plastic	S	0%	10	V_s =	0%	0	W_s =	0
Soil	ND	0%		V_n =	0%		W_n =	0
Glass	ND	0%						
Decomposable Moist Wt=			100	V_t =	100%	60	Dry Wt	

V_i = Volume of Type of Waste W_i = Weight of Constituent (based on 100 lb sample)

For 100lb wet sample, wet weight = % of MSW

Average moisture content of waste, m.c. = 40%

For 100lb wet sample, weight of water = W_{tot} x m.c. = 0.4 * 100lb = 40 lb

Wt of decomposable fraction - all water contained in waste= 100 - 40 lb = 60 lb

STEP 2

Step 2: Determine Lambda Factors Characteristic equation: $V_{ti} = V_i\, e^{-(\lambda it)}$

λ_r = 0.1386

λ_m = *0.0231** (*not used since only readily waste considered)

λs = *0.0173** (*not used since only readily waste considered)

STEP 3

Step 3: Select year of interest to determine modifier, V_i (t=173 years)

For this example, use 30 year

Readily: V_r@173yrs = (100%) $e^{-[(0.1386)(173)]}$ = 3.859E-09

Moderately: V_m@173yrs = (0%) $e^{-[(0.0231)(173)]}$ = - (see * note above)

Slowly: V_s@173yrs = (0%) $e^{-[(0.0173)(173)]}$ = - (see * note above)

STEP 4

Step 4: Determine % decomposed

% decomposed = $(V_i - V_{it})/V_i$

Readily: $\%D_r$ = (1.0-(3.859E-09))/1.0 x 100% = 100%

Moderately: $\%D_m$ = 0* -

Slowly: $\%D_s$ = 0* -

STEP 5

Step 5: Determine (dry) weight of decomposed wastes

Weight of decomposed weight = % decomposed x dry weight fraction

Readily: 100% x (60.00 lb) 60 lb

Moderately: 0* 0 lb

Slowly: 0* 0 lb

Total decomposed weight= 60.00 lb

Table G.2 Calculation for Theoretical Maximum Gas Production for Readily Degradable Bioreactors by Lambda Method (continued)

STEP 6	**Step 6: Determine gas produced using stoichiometric reaction masses** Reaction Masses from stoichiometry $C_aH_bO_cN_d$ = 475.7 CH_4 = 170.27 NH_3 = 17 H_2O = 127.0 CO_2 = 415.34
STEP 7	**Step 7: Determine volume of gas produced up to time, *t*** (173 years for example) Volume methane produced, $V_{CH4} = (M_{CH4})(W_{degraded}) / [(M_{CaHbOcNd})(W_{CH4})$ V_{CH4} = [(170.27)(60)] / [(475.7)(0.0448)] = 479.37 ft^3 V_{CO2} = [(415.34)(60)] / [(475.7)(0.1234)] = 424.53 ft^3 Total gas, $V_{total} = V_{CH4} + V_{CO2}$ = 903.9 ft^3 % CH4 = 53% %CO_2 = 47% Theoretical gas produced per lb waste up to 173 years= V_{total}/sample weight At end of practical biodegradation, theoretical total gas produced = Gas production at time t (173 years) = 903.9 ft^3/100lb = **9.04** ft^3/lb

Table G.3 Calculation for Theoretical Maximum Gas Production for Moderately Bioreactors by Lambda Method

TEP 1

Step 1: Break out composition into % descriptive modifiers

Inputted				Calculated				
Waste	Type	% MSW	Wet Wt [lb]	V_i	% of Type	Dry weight	W_i [lb]	Wt of Type
Food	R	0%	0	V_r =	0%	0	W_r =	0
Yard Waste	R	0%	0			0		
Wood	M	5%	0	V_m =	100%	3.00	W_m =	60
Paper	M	88%	0			53.40		
Textiles	M	7%	0			3.60		
Plastic	S	0%	0	V_s =	0%	0	W_s =	0
Soil	ND	0%		V_n =	0%	0	W_n =	0.00
Glass	ND	0%				0		
Decomposable Moist Wt=			100	V_t =	100%	60	Dry Wt	

V_i = Volume of Type of Waste W_i = Weight of Constituent (based on 100 lb sample)

Average moisture content of waste, m.c. = 40%

For 100lb wet sample, weight of water = W_{tot} x m.c. = 0.4 * 100lb = 40 lb

Wt of decomposable fraction - all water contained in waste= 100 - 40 lb = 60 lb

STEP 2

Step 2: Determine Lambda Factors   Characteristic equation: $V_{ti} = V_i\, e^{-(\lambda it)}$

λ_r = *0.1386** (*not used since only moderately waste considered)

λ_m = 0.0231

λs = *0.0173** (*not used since only moderately waste considered)

STEP 3

Step 3: Select year of interest to determine modifier, V_i (t=173 years)

For this example, use 173 year

Readily: V_r@173yrs = (0%) $e^{-[(0.1386)(173)]}$ = 0

Moderately: V_m@173yrs = (100%) $e^{-[(0.0231)(173)]}$ = 1.84E-02

Slowly: V_s@173yrs = (0%) $e^{-[(0.0173)(173)]}$ = 0

STEP 4

Step 4: Determine % decomposed

% decomposed = $(V_i - V_{it})/V_i$

Readily: $\%D_r$ = 0* 0

Moderately: $\%D_m$ = (1-(1.84E-02))/1 x 100% = 98%

Slowly: $\%D_s$ = 0* 0

STEP 5

Step 5: Determine (dry) weight of decomposed wastes

Weight of decomposed weight = % decomposed x dry weight fraction

Readily: 0* lb

Moderately: 98% x 60.00 lb 58.8 lb

Slowly: 0* lb

Total decomposed weight= 58.8 lb

Table G.3 Calculation for Theoretical Maximum Gas Production for Moderately Degradable Bioreactors by Lambda Method (continued)

STEP 6	**Step 6: Determine gas produced using stoichiometric reaction masses** Reaction Masses from stoichiometry $C_aH_bO_cN_d$ = 2269.4 CH_4 = 739.4 NH_3 = 17 H_2O = 21.65 CO_2 = 1903.1
STEP 7	**Step 7: Determine volume of gas produced up to time, *t*** (173 years for example) Volume methane produced, $V_{CH4} = (M_{CH4})(W_{degraded}) / [(M_{CaHbOcNd})(W_{CH4})$ V_{CH4} = [(739.4)(58.8)] / [(2269.4)(0.0448)] = 427.63 ft^3 V_{CO2} = [(1903.1)(58.8)] / [(2269.4)(0.1234)] = 399.59 ft^3 Total gas, $V_{total} = V_{CH4} + V_{CO2}$ = 827.22 ft^3 % CH4 = 52% %CO_2 = 48% Theoretical gas produced per lb waste up to 173 years= V_{total}/sample weight At end of practical biodegradation, theoretical total gas produced = Gas production at time t (173 years) = 827.22 ft^3/100lb = **8.27** **ft^3/lb**

Table G.4 Calculation for Theoretical Maximum Gas Production for Slowly Degradable Bioreactors by Lambda Method

TEP 1

Step 1: Break out composition into % descriptive modifiers

Inputted				Calculated				
Waste	Type	% MSW	Wet Wt [lb]	V_i	% of Type	Dry weight	W_i [lb]	Wt of Type
Food	R	0%	0	V_r =	0%	0	W_r =	0
Yard Waste	R	0%	0			0		
Wood	M	0%	0	V_m =	0%	0	W_m =	0
Paper	M	0%	0			0		
Textiles	M	0%	0			0		
Plastic	S	100%	100	V_s =	100%	60	W_s =	60
Soil	ND	0%		V_n =	19%		W_n =	0.00
Glass	ND	0%						
Decomposable Moist Wt=			100	V_t =	100%	60.00	Dry Wt	

V_i = Volume of Type of Waste W_i = Weight of Constituent (based on 100 lb sample)

For 100lb wet sample, wet weight = % of MSW

Average moisture content of waste, m.c. = 40%

For 100lb wet sample, weight of water = W_{tot} x m.c. = 0.4 * 100lb = 40 lb

Wt of decomposable fraction - all water contained in waste= 100 - 40 lb = 60 lb

STEP 2

Step 2: Determine Lambda Factors   Characteristic equation: $V_{ti} = V_i\, e^{-(\lambda it)}$

λ_r = *0.1386* (*not used since only slowly waste considered)

λ_m = *0.0231* (*not used since only slowly waste considered)

λs = 0.0173

STEP 3

Step 3: Select year of interest to determine modifier, V_i (t=173 years)

For this example, use 173 year

Readily: V_r@173yrs = (0%) $e^{-[(0.1386)(173)]}$ = 0*

Moderately: V_m@173yrs = (0%) $e^{-[(0.0231)(173)]}$ = 0*

Slowly: V_s@173yrs = (100%) $e^{-[(0.0173)(173)]}$ = .05014

STEP 4

Step 4: Determine % decomposed

% decomposed = $(V_i - V_{it})/V_i$

Readily: $\%D_r$ = 0* -

Moderately: $\%D_m$ = 0* -

Slowly: $\%D_s$ = (1-(.0504))/1 x 100% = 95%

STEP 5

Step 5: Determine (dry) weight of decomposed wastes

Weight of decomposed weight = % decomposed x dry weight fraction

Readily: 0* 0 lb

Moderately: 0* 0 lb

Slowly: 95% x (60 lb) 57.0 lb

Total decomposed weight= 57.0 lb

Table G.4 Calculation for Theoretical Maximum Gas Production for Slowly Degradable Bioreactors by Lambda Method (continued)

STEP 6	**Step 6: Determine gas produced using stoichiometric reaction masses** Reaction Masses from stoichiometry $C_aH_bO_cN_d$ = 1.89 CH_4 = 1.02 NH_3 = 17 H_2O = 0.95 CO_2 = 1.81
STEP 7	**Step 7: Determine volume of gas produced up to time, *t*** (30 years for example) Volume methane produced, $V_{CH4} = (M_{CH4})(W_{degraded}) / [(M_{CaHbOcNd})(W_{CH4})$ V_{CH4} = [(1.02)(57)] / [(1.89)(0.0448)] = 686.65 ft^3 V_{CO2} = [(1.81)(57)] / [(1.89)(0.1234)] = 442.36 ft^3 Total gas, $V_{total} = V_{CH4} + V_{CO2}$ = 1129.01 ft^3 % CH4 = 61% %CO_2 = 39% Theoretical gas produced per lb waste up to 173 years= V_{total}/sample weight At end of practical biodegradation, theoretical total gas produced = Gas production at time t (173 years) = 1,129 ft^3/100lb = **11.29*** **ft^3/lb**

*As discussed in Section 6.1.5, the author and several others (Shah et. al 2007, Ishigaki et al. 2003, Tchobanoglous 1993, Albertson et. al, 1987) note that the inability to use of stoichiometric and mathematical models to predict the gas for plastics (noted with asterisk above). It is observed that theoretical gas production for slowly decomposable wastes is most accurately described by comparison of total gas collected and measurement of actual mass degradation.

G.2 Calculations to Determine End of Experiment

The author indicates that the date for conclusion of this experiment was based on an evaluation of the total gas production and rate of gas production. The author used an analytical approach suggested by Raghu (2014) as described in Chapter 5.1.1 to determine the practical amount of gas which could be collected, and to extrapolate the rate of gas production to determine the maximum gas which could be collected, $y_{max\text{-}actual}$, if the experiment was held until the end of biodegradation occurred. A calculation for the composite flow meter is provided in Chapter 5.1.1. Calculations based on data from the readily degradable flow meter are presented as Figure G.1 through G.4. Calculations based on data from the moderately flow meter are presented as Figure G.5 through G.8.

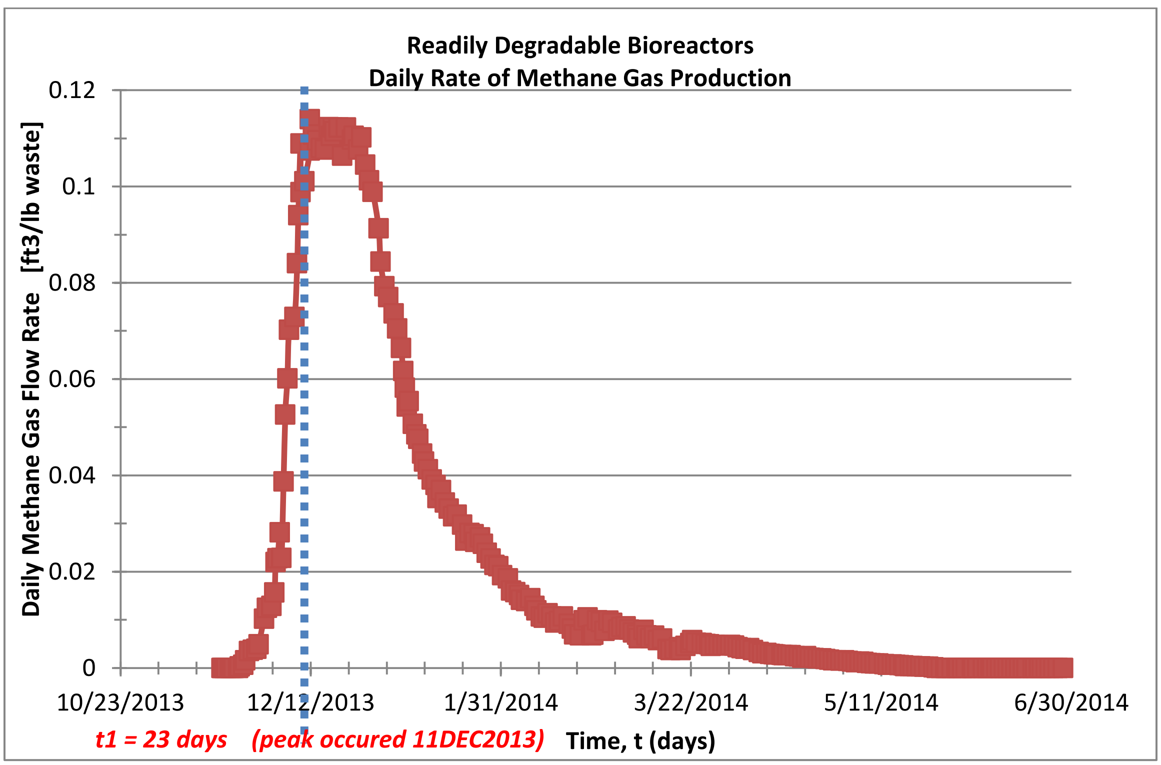

Figure G.1 Daily Rate of Gas Production for Determination of End Of Experiment – Readily Degradable Bioreactors

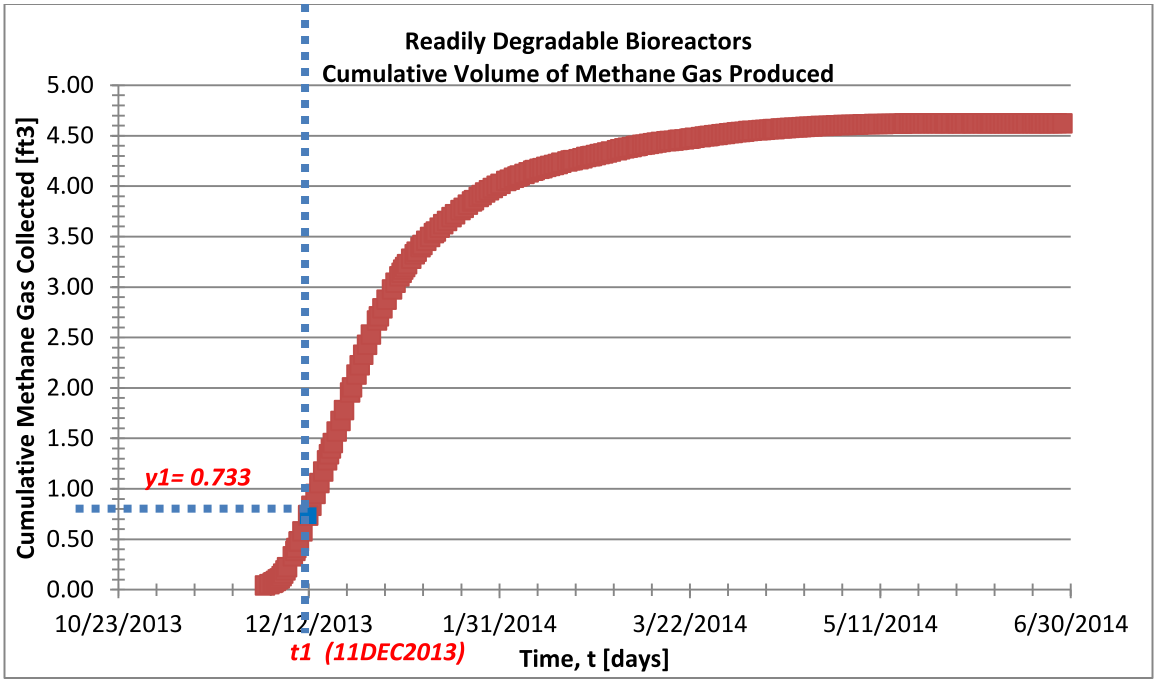

Figure G.2 Cumulative Gas Production for Determination of End of Experiment – Readily Degradable Bioreactors

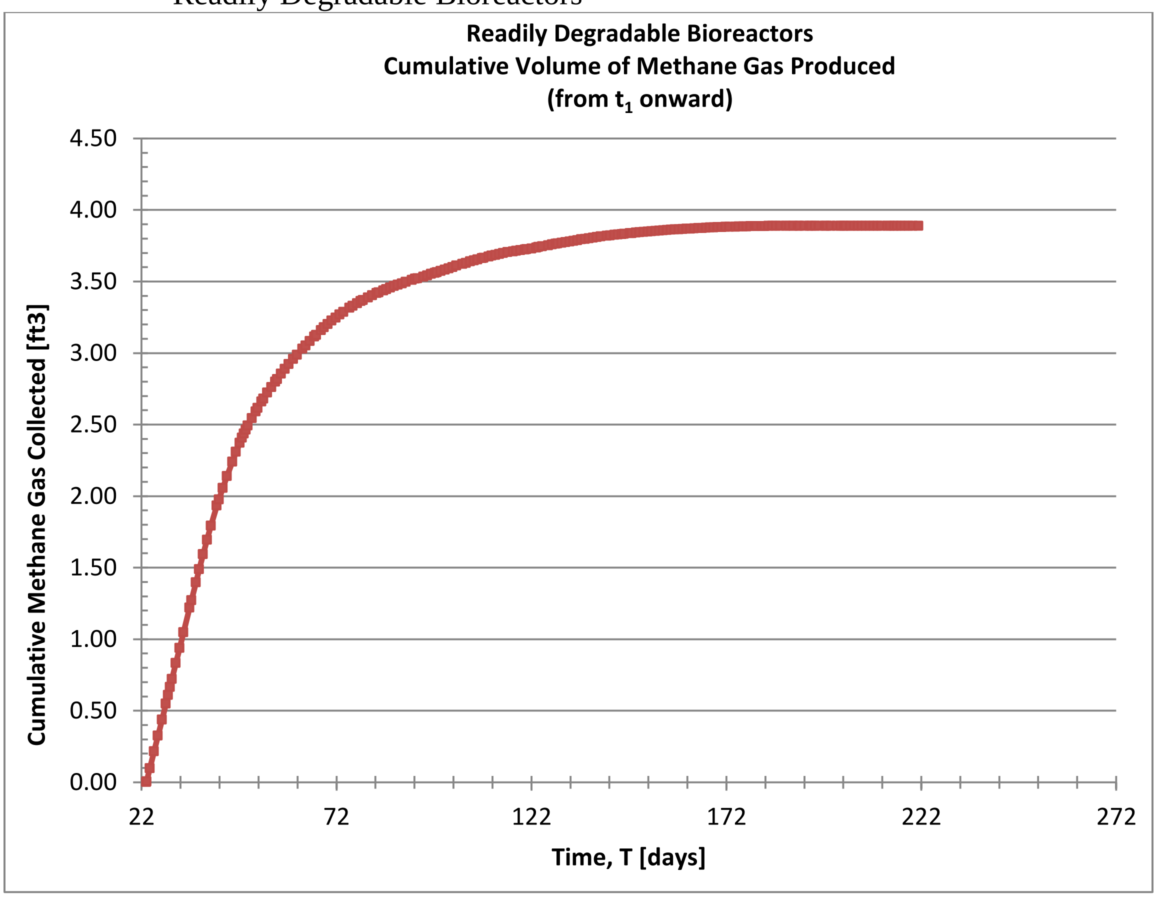

Figure G.3 Cumulative Gas Production for Determination of End of Experiment – Readily Degradable Bioreactors

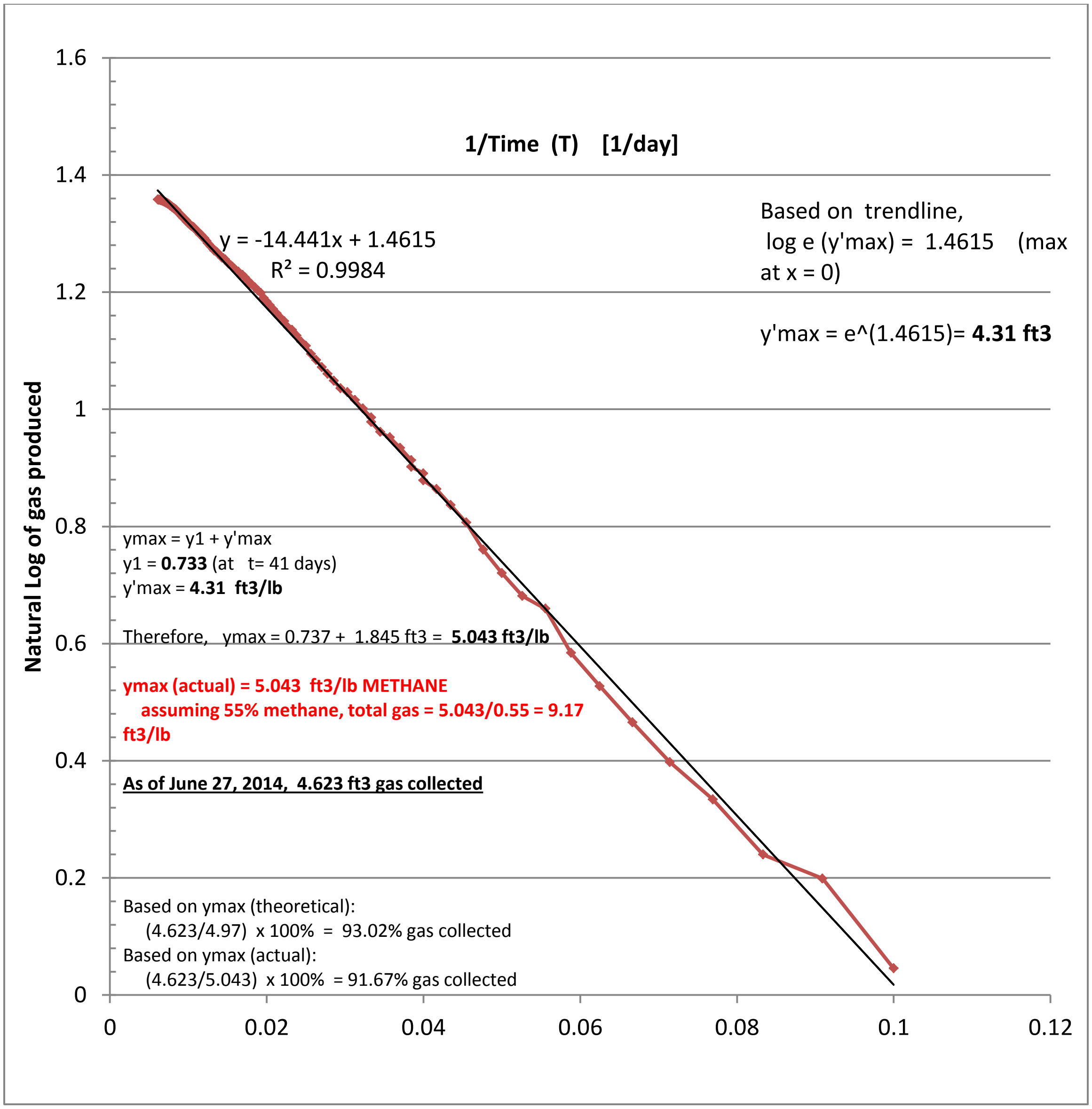

Figure G.4 Determination of y_{max}-actual – Readily Degradable Bioreactors

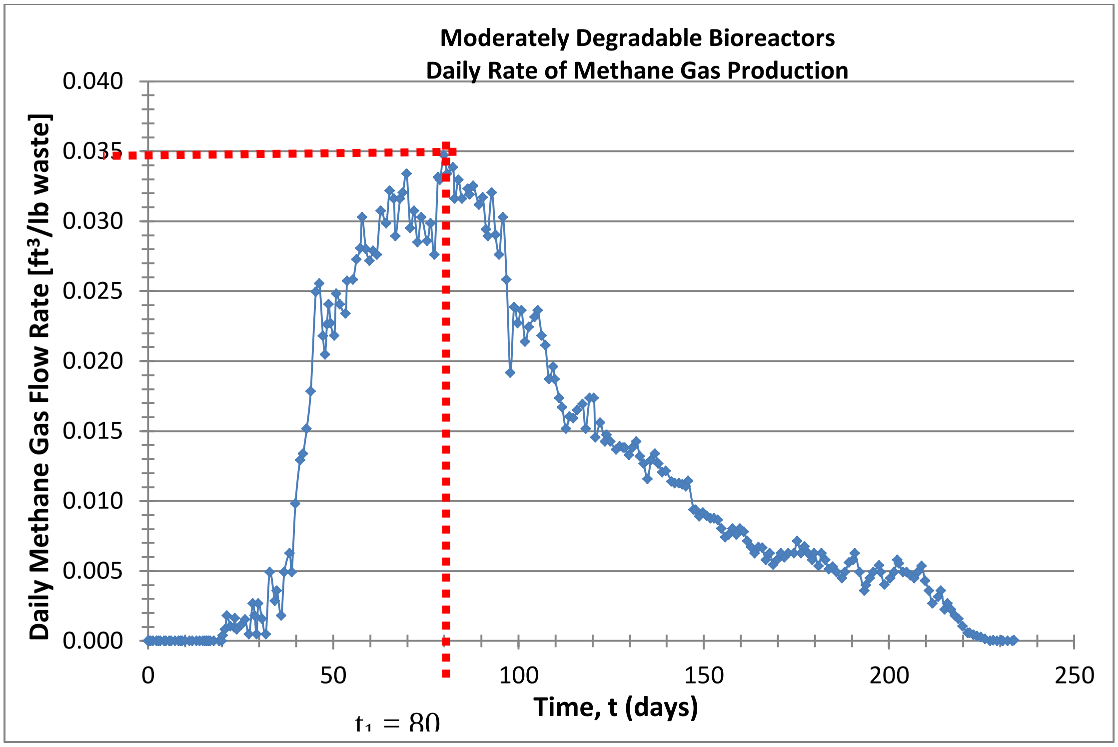

Figure G.5 Daily Rate of Gas Production for Determination of End of Experiment – Moderately Degradable Bioreactors

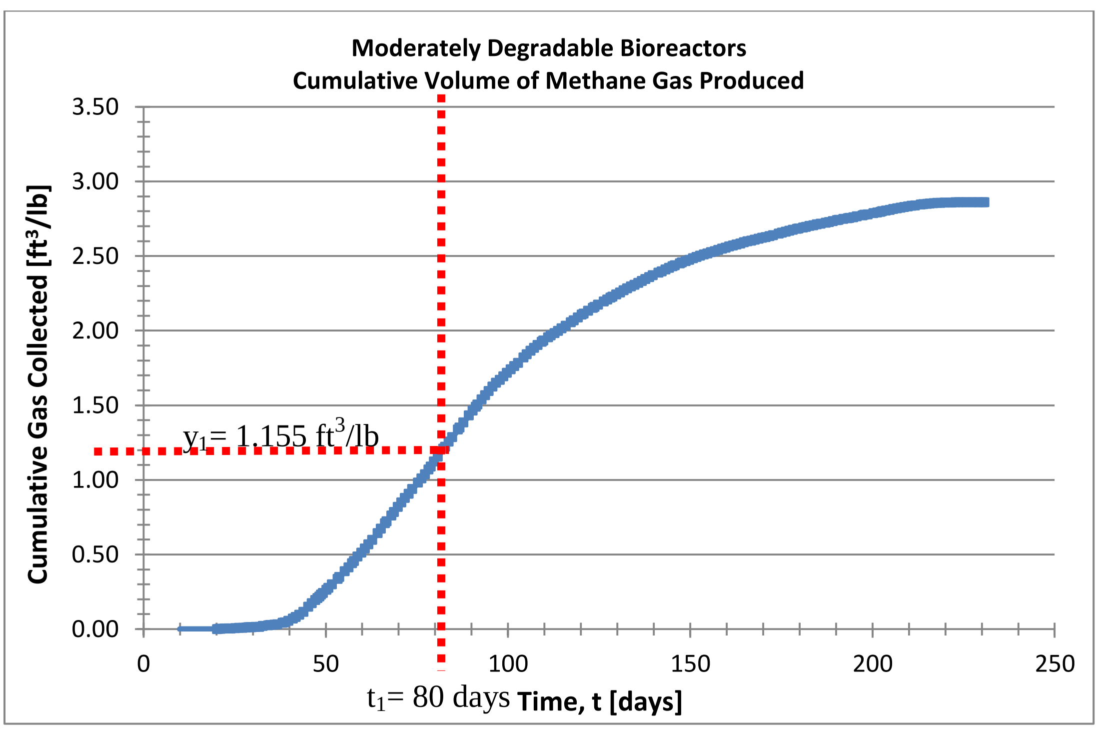

Figure G.2 Cumulative Gas Production for Determination of End of Experiment – Moderately Degradable Bioreactors

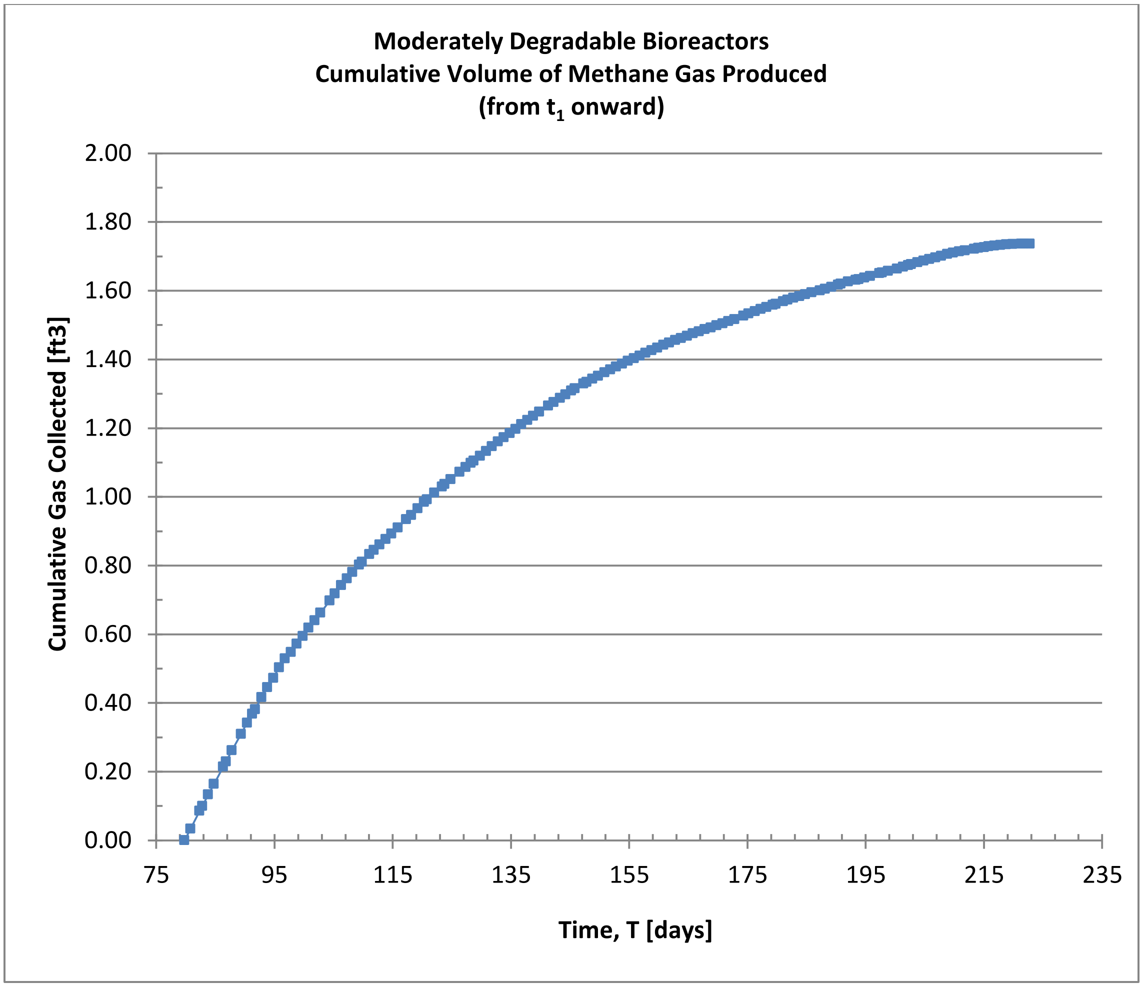

Figure G.3 Cumulative Gas Production for Determination of End of Experiment – Moderately Degradable Bioreactors

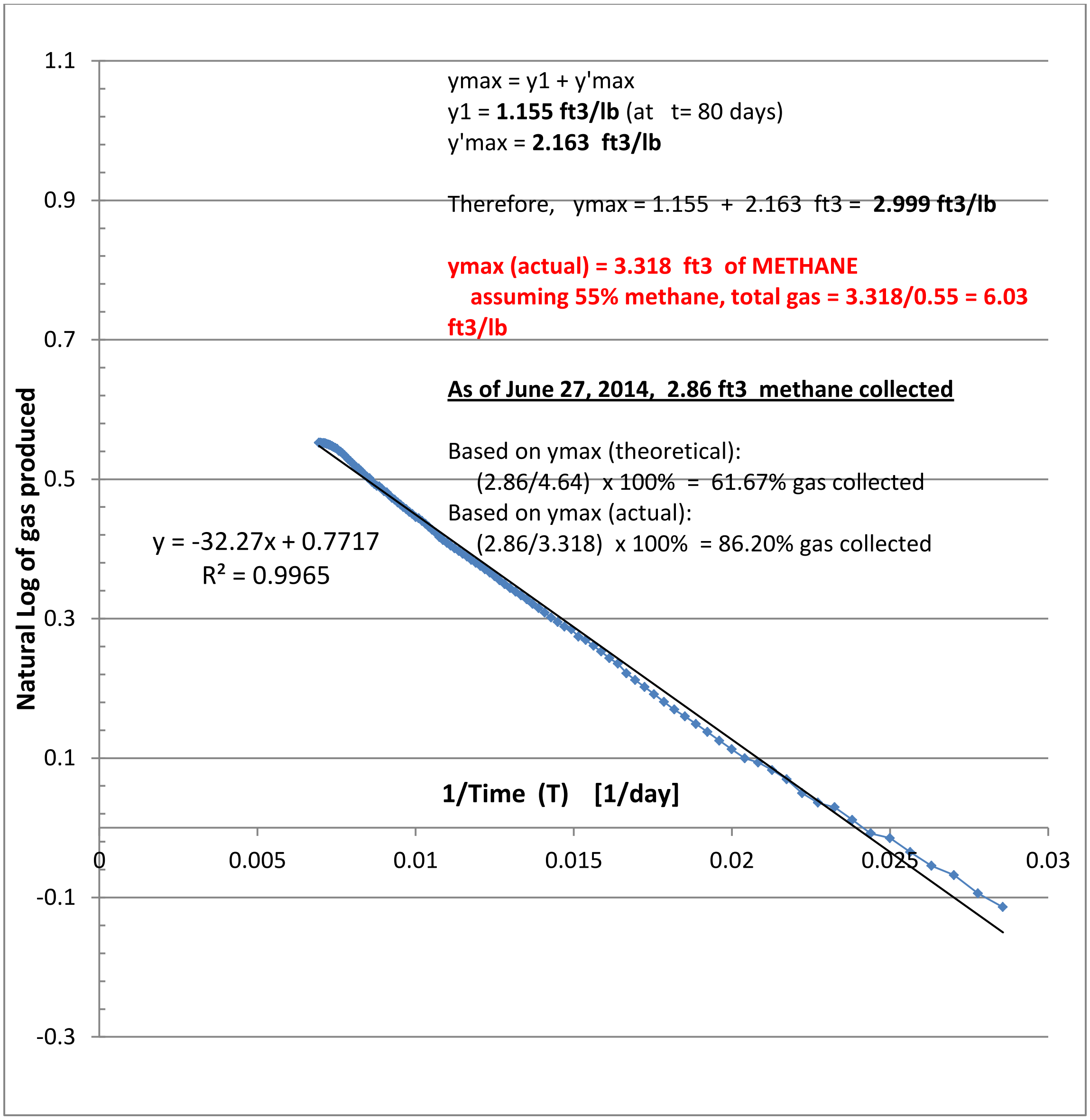

Figure G.4 Determination of y_{max}-actual – Moderately Degradable Bioreactors

APPENDIX H

DATA AND CALCULATIONS FOR FIELD VALIDATION

The following data was provided and used for the field validation model of the CMCMUA Cell “E” bioreactor landfill and Yolo County, California bioreactor landfill. Calculations to support the use of the model are also presented herein.

H.1 Topographic and Tonnage Data for CMCMUA Bioreactor Landfill

To support the use of the proposed model, it was anticipated that information regarding the waste composition, incoming tonnage records, and topographic data would be required, at minimum, for the cell. The data is presented throughout the following figures.

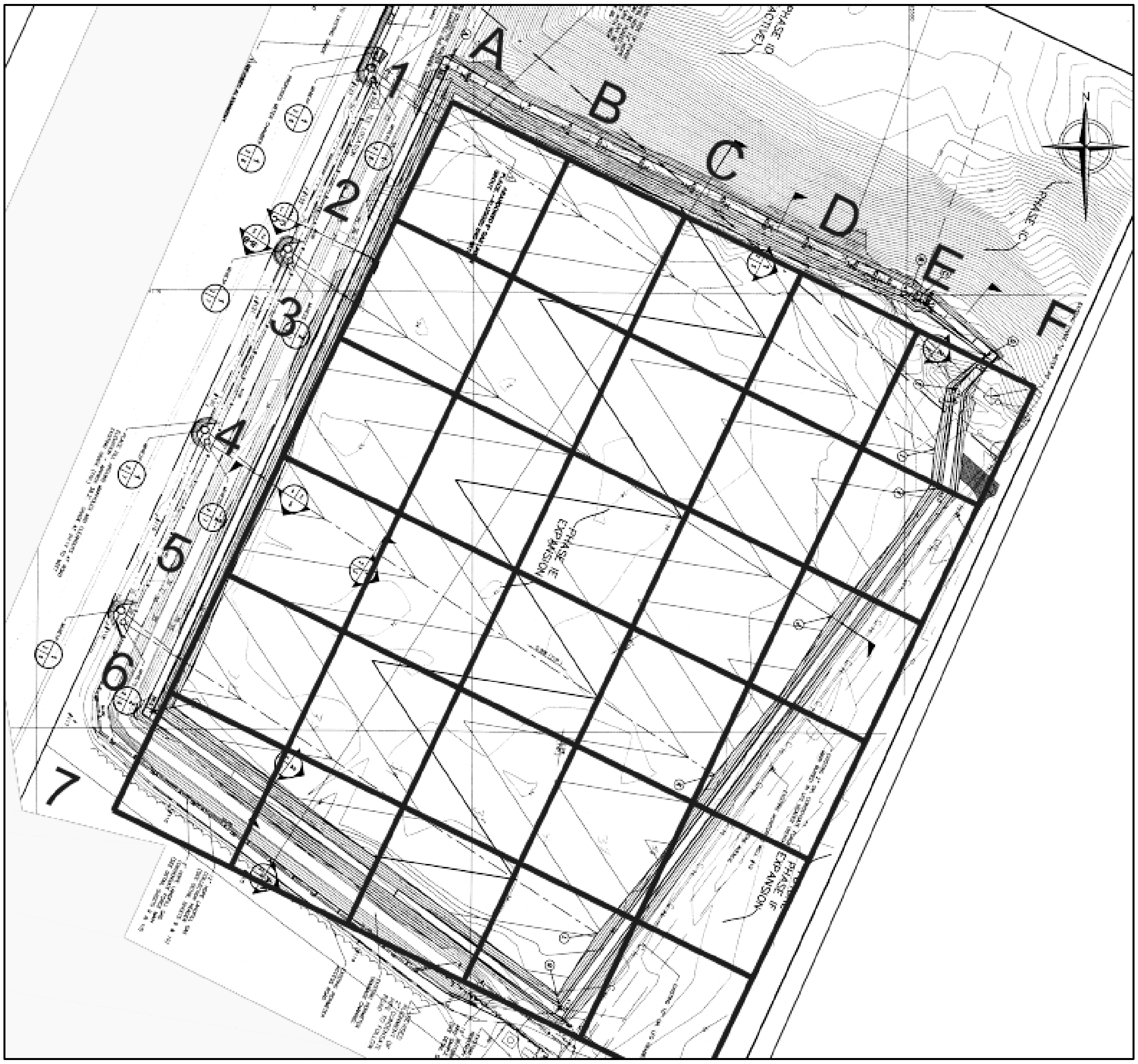

Figure H.1 Base Liner Topographic Survey (2003 Year) and Grid for CMCMUA Cell E

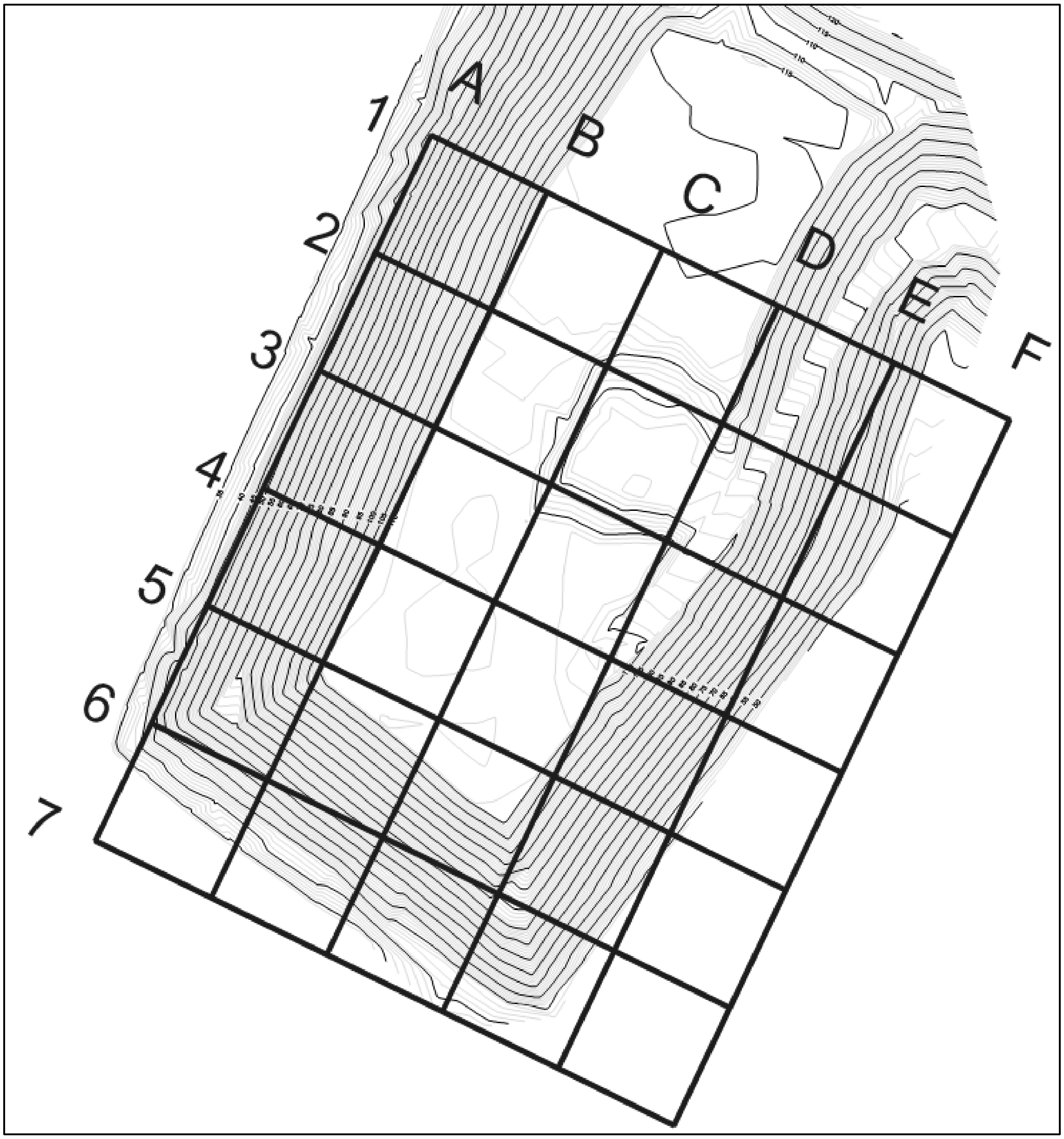

Figure H.2 Closure Topographic Survey (2007 Year) and Grid for CMCMUA Cell E

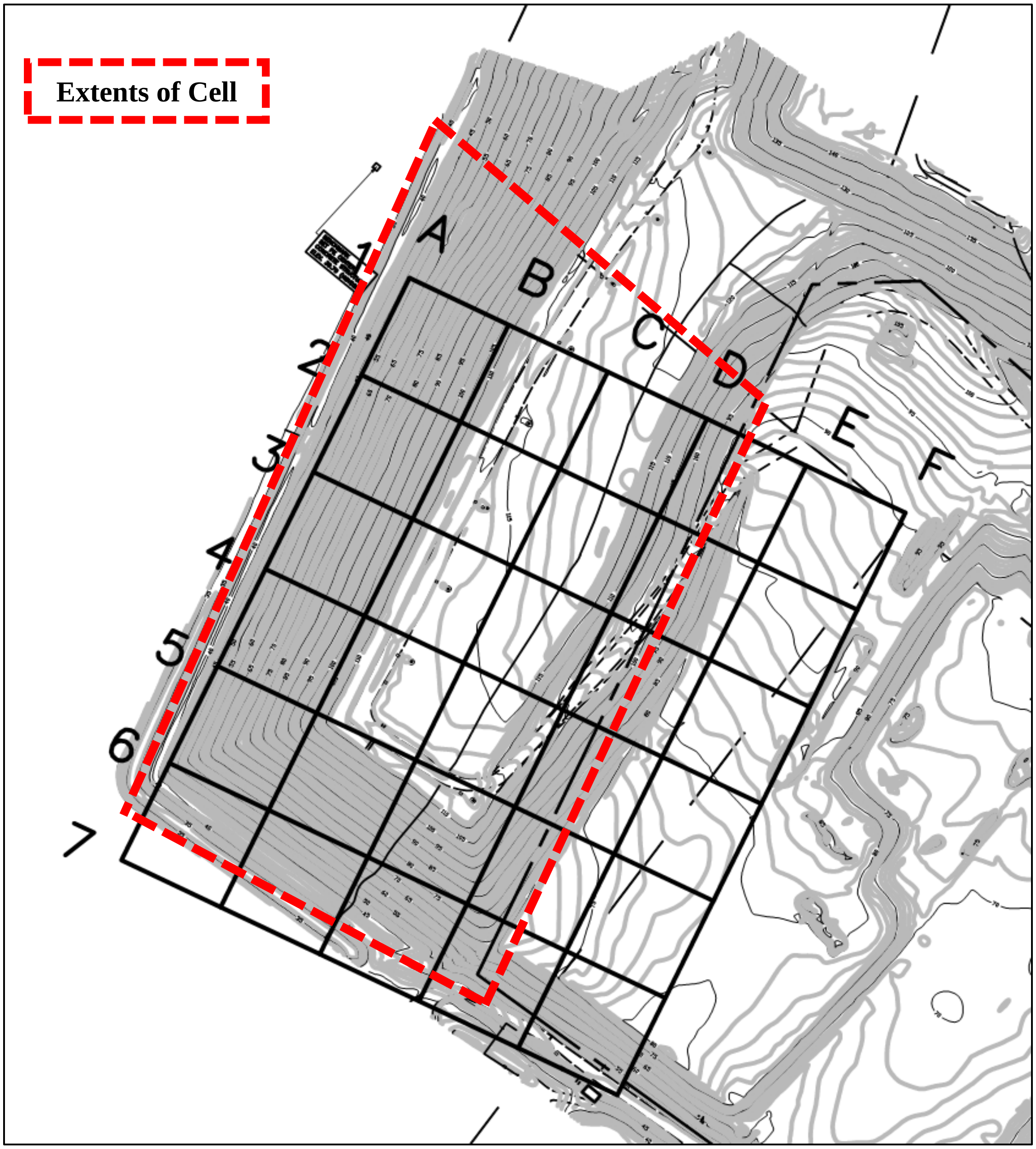

Figure H.3 Annual Topographic Survey (2012 Year) and Grid for CMCMUA Cell E

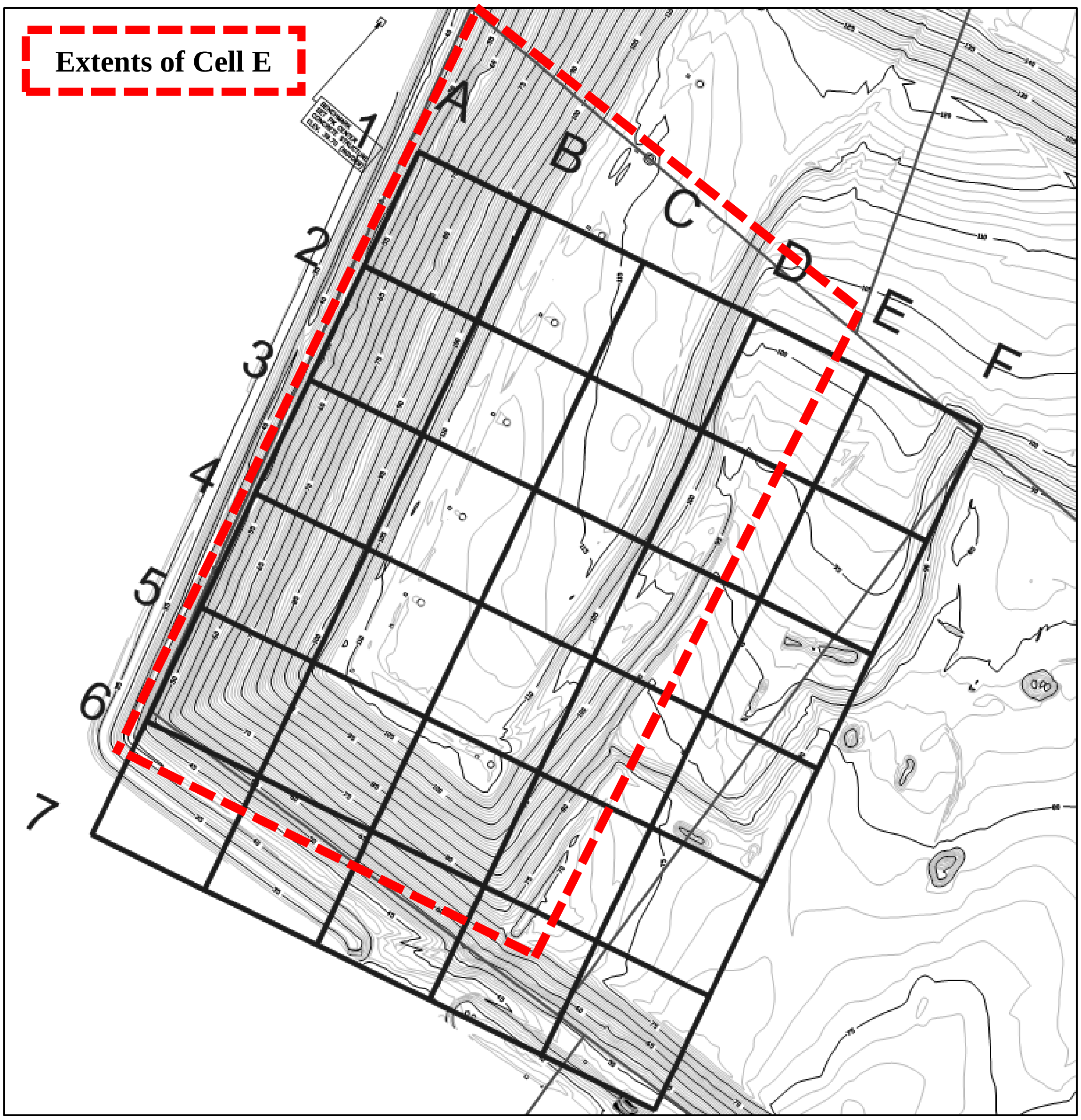

Figure H.4 Annual Topographic Survey (2013 Year) and Grid for CMCMUA Cell E

YEARLY TONNAGE SUMMARY FOR THE SANITARY LANDFILL

SOLID WASTE		2000	2001	2002	2003	2004
Mun. Waste/ACUA	10AC					
Mun. Waste	10	94,856.72	92,811.76	96,301.24	101,534.24	104,743.19
Mun Waste, Contam.	10C	1.65	3.95	0.00	5.59	
Mun Waste, Car	10CA	135.32	148.28	172.33	142.64	61.36
Road Litter, free	10F	12.31	4.76	9.04	20.65	31.45
Total Type 10		95,006.00	92,968.75	96,482.61	101,703.02	104,836.00
*Bulky Waste	13	6,329.45	5,543.86	5,628.18	5,901.80	6,625.65
*Bulky Waste, C&D	13C	66,827.92	75,289.09	87,210.93	109,041.39	128,832.00
*Bulky Waste, Car	13CA	43.64	53.82	55.72	30.16	4.58
*Bulky Waste ,Free	13F	44.23	3.40	2.69	12.61	1.56
*Bulky Waste, Litter Abatemei	13LA	696.69	886.32	568.99	751.91	526.72
*Bulky Waste,Pickup	13P			0.00	0.00	0.00
*Bulky Waste,Storm Debris	13SD	70.97	0.00	21.18	0.00	0.00
Bulky c Tires	13T	20.30	42.61	0.00	1.47	16.67
Total Type 13		74,033.20	81,819.00	93,487.69	115,739.34	136,007.18
Contam. Veg.,Car	23CA	1.99	1.60	3.10	3.02	0.00
Contam. Veg.	23	766.74	281.78	243.07	197.79	116.21
Contam. Veg.Free	23F	0.10	0.00	0.00	0.00	0.00
Animal & Food	25	581.95	596.80	717.39	788.64	598.01
Dog Warden	25A	0.33	0.39	0.22	10.61	0.63
Non-Haz Indust.	27	1,620.81	1,137.96	978.37	1,144.48	939.63
Non-Haz-Pickup	27P	0.00	0.00	0.00	0.00	0.00
Asbestos	27A	712.38	1,008.40	1,122.41	1,377.86	1,508.05
Asbestos,Free	27AF	0.00	0.00	0.00	0.00	0.00
IPF Residue	IPF	2,037.67	2,877.47	2,307.60	2,321.75	1,670.87
Total Other Commodities		5,721.97	5,904.39	5,372.16	5,844.15	4,833.40
*SLUDGE(accepted 1984-1986)						
Total Solid Waste		174,761.17	180,692.14	195,342.46	223,286.51	245,676.58
RECYCLING						
Mixed Paper	12	18,179.02	17,294.10	17,297.18	16,792.99	16,430.09
Mixed Paper, Car	12CA	2.15	2.45	4.39	2.28	0.15
Old Corrugated Commercial	12OC					
Commingled	18	11,771.92	16,989.82	15,668.72	17,164.58	17,347.08
MRP	MRP					
Comingled, Car	18CA	1.00	0.65	0.61	0.31	0.00
Total to IPF		29,954.09	34,287.02	32,970.90	33,960.16	33,777.32
Recyclable Soil	FCC/27E	444.23	653.62	414.01	1,643.14	2,395.31
Scrap Metal	SM	482.72	479.34	552.15	442.34	333.52
Wood Waste	13W	1,330.89	0.00	0.00	0.00	0.00
Electronics	EL					
FILM	FILM					
Mixed Rigid Plastics	MRP					
CFC/White Goods	CFC					389.05
White Goods	13WG	501.63	627.53	693.08	636.42	138.55
Wood Pallets-Contract	CHIP	3,541.19	2,791.78	2,078.72		4,477.29
Wood Pallets	13WP	3,392.46	3,944.41	3,186.58	5,000.82	632.27
5 Tires Free	13TF	0.00	227.83	66.51	0.00	0.00
Tires/SSCF Reef	13TR	0.00	0.00	0.00	0.00	0.00
Tires/Stockpile	13SR	556.35	331.10	194.34	223.59	177.35
Tires Special Projects	13SP					
Tires Oversized	13TL					
Leaves & Grass Clippings	23C	5,385.21	7,039.75	7,114.06	6,358.88	5,058.26
Brush, Branches & Stumps	23H	2,537.42	3,092.61	2,676.24	2,689.82	3,719.17
Stumps & Tree Trunks	23S	753.98	0.00	0.00	1,085.54	1,360.59
Xmas Trees	23T	82.60	118.97	98.06	88.93	61.90
COVER						72,415.33
Catch Basin	27C	1,177.92	863.32	217.81	176.36	249.43
St. Sweepings	27S	5,066.90	4,340.04	4,694.87	4,967.52	4,862.71
Chipped Chips	CC					
OBGM Mixed Glass	mglassc					
Total Recycling Tons		55,207.59	58,797.32	54,957.33	57,273.52	130,048.05
ALL TONS		229,968.76	239,489.46	250,299.79	280,560.03	375,724.63

Figure H.5 Tonnage records and waste characterization for 2000 through 2004 years for CMCMUA Landfill
Source: Cape May County Municipal Utilities Authority (used with permission)

YEARLY TONNAGE SUMMARY FOR THE SANITARY LANDFILL

SOLID WASTE		2005	2006	2007	2008	2009
Mun. Waste/ACUA	10AC					
Mun. Waste	10	105,309.01	104,162.56	97,965.45	91,906.82	90,830.35
Mun Waste, Contam.	10C	1.58	6.43		0.00	
Mun Waste, Car	10CA	3.76	0.15	0.18	0.15	0.03
Road Litter, free	10F	8.30	40.25	13.23	7.83	5.00
Total Type 10		105,322.65	104,209.39	97,978.86	91,914.80	90,835.38
*Bulky Waste	13	7,429.07	8,822.53	14,268.18	14,423.79	11,206.44
*Bulky Waste, C&D	13C	132,326.47	100,784.71	67,619.23	54,267.87	47,690.52
*Bulky Waste, Car	13CA	0.81	0.05	0.05	0.00	0.00
*Bulky Waste ,Free	13F	11.32	6.81	7.06	2.35	3.89
*Bulky Waste, Litter Abateme	13LA	665.77	707.00	643.80	389.47	443.49
*Bulky Waste,Pickup	13P	0.00		0.00	0.00	0.00
*Bulky Waste,Storm Debris	13SD	0.00		0.00	0.00	0.00
Bulky c Tires	13T	18.69	11.57	0.00	6.37	0.00
Total Type 13		140,452.13	110,332.67	82,538.32	69,089.85	59,344.34
Contam. Veg.,Car	23CA	0.00	0.00	0.00	0.00	0.00
Contam. Veg.	23	186.13	123.36	136.69	340.34	74.58
Contam. Veg.Free	23F	0.00	3.30	0.00	7.73	1.38
Animal & Food	25	922.94	1,098.64	1,236.00	1,621.66	1,995.64
Dog Warden	25A	0.00	0.00	0.00	0.00	0.00
Non-Haz Indust.	27	1,130.49	1,343.86	1,077.36	8,780.25	2,094.75
Non-Haz-Pickup	27P	0.00		0.00	0.00	0.00
Asbestos	27A	1,587.55	947.14	643.14	545.98	366.24
Asbestos,Free	27AF	0.00	0.24	0.17	0.00	14.52
IPF Residue	IPF	1,897.66	1,796.81	1,727.62	1,433.52	1,673.23
Total Other Commodities		5,724.77	5,312.35	4,820.98	12,729.48	6,220.34
*SLUDGE(accepted 1984-1986)						
Total Solid Waste		251,499.55	219,854.41	185,338.16	173,734.13	156,400.06
RECYCLING						
Mixed Paper	12	16,391.50	16,400.34	15,808.48	14,990.87	13,903.46
Mixed Paper, Car	12CA	0.00			0.01	0.01
Old Corrugated Commercial	12OC					
Commingled	18	18,373.38	17,808.94	18,356.70	18,267.18	18,487.15
MRP	MRP		6.61	10.78	13.16	2.26
Comingled, Car	18CA	0.01				0.01
Total to IPF		34,764.89	34,215.89	34,175.96	33,271.22	32,392.89
Recyclable Soil	FCC/27E	959.73	2,296.05	1,718.18	67.30	102.95
Scrap Metal	SM	266.09	176.73	91.23	75.39	95.30
Wood Waste	13W	0.00	0.00	0.00	0.00	0.00
Electronics	EL		36.92	113.99	259.27	283.04
FILM	FILM				16.47	22.30
Mixed Rigid Plastics	MRP				72.90	106.65
CFC/White Goods	CFC	295.49	165.37	94.31	54.21	60.53
White Goods	13WG	104.98	93.45	41.21	28.10	23.75
Wood Pallets-Contract	CHIP	4,632.12	5,940.88	5,509.45	4,453.92	3,423.84
Wood Pallets	13WP	850.99	921.91	869.22	2,276.49	1,425.55
5 Tires Free	13TF	0.00				
Tires/SSCF Reef	13TR	0.00				
Tires/Stockpile	13SR	216.21	265.41	152.09	175.65	143.76
Tires Special Projects	13SP					
Tires Oversized	13TL					
Leaves & Grass Clippings	23C	6,745.96	8,228.22	7,541.48	10,205.17	10,792.99
Brush, Branches & Stumps	23H	5,164.87	4,180.44	2,977.84	3,198.27	2917..49
Stumps & Tree Trunks	23S	1,117.25	2,410.74	1,771.20	792.59	790.90
Xmas Trees	23T	69.32	95.19	43.00	33.34	29.87
COVER		37,744.60	38,730.99	52,091.26	36,855.29	19,357.00
Catch Basin	27C	288.20	222.53	306.66	472.83	211.44
St. Sweepings	27S	4,803.69	5,178.15	5,245.66	5,314.26	4,603.74
Chipped Chips	CC					
OBGM Mixed Glass	mglassc					
Total Recycling Tons		98,024.39	103,158.87	112,742.74	97,622.67	73,866.50
ALL TONS		349,523.94	323,013.28	298,080.90	271,356.80	230,266.56

Figure H.6 Tonnage records and waste characterization for 2005 through 2009 years for CMCMUA Landfill

Source: Cape May County Municipal Utilities Authority (used with permission)

H.2 Waste Characterization for Yolo County, California

Data regarding waste characterization for the waste which was deposited into within the Yolo County bioreactor used for the field validation model is provided as Figure H.7.

Table ES - 3: Composition of the Overall Disposed Waste Stream by Material Type

	Est. Pct.	+ / -	Est. Tons
Paper	**30.2%**		**10,742,707**
Uncoated Corrugated Cardboard	4.6%	0.2%	1,630,348
Paper Bags	0.7%	0.0%	261,563
Newspaper	4.3%	0.3%	1,521,186
White Ledger Paper	2.3%	0.2%	812,752
Colored Ledger Paper	0.2%	0.0%	60,270
Computer Paper	0.3%	0.1%	114,545
Other Office Paper	1.7%	0.2%	591,080
Magazines and Catalogs	1.9%	0.1%	669,434
Phone Books and Directories	0.3%	0.1%	99,793
Other Miscellaneous Paper	4.4%	0.2%	1,565,454
Remainder/Composite Paper	9.6%	0.4%	3,416,281
Glass	**2.8%**		**1,011,441**
Clear Glass Bottles & Containers	1.4%	0.1%	506,214
Green Glass Bottles & Containers	0.4%	0.1%	154,191
Brown Glass Bottles & Containers	0.5%	0.0%	167,529
Other Colored Glass Bottles & Containers	0.0%	0.0%	6,859
Flat Glass	0.1%	0.0%	23,206
Remainer/Composite Glass	0.4%	0.1%	153,443
Metal	**6.1%**		**2,164,080**
Tin/Steel Cans	1.0%	0.1%	339,570
Major Appliances	0.1%	0.0%	23,257
Other Ferrous Metal	2.4%	0.3%	866,716
Aluminum Cans	0.2%	0.0%	87,086
Other Non-Ferrous Metal	0.3%	0.0%	93,548
Remainder/Composite Metal	2.1%	0.3%	753,903
Plastic	**8.9%**		**3,161,711**
HDPE Containers	0.8%	0.0%	275,944
PETE Containers	0.5%	0.0%	160,615
Miscellaneous Plastic Containers	0.7%	0.1%	239,954
Film Plastic	3.9%	0.2%	1,377,438
Durable Plastic Items	1.8%	0.2%	631,536
Remainder/Composite Plastic	1.3%	0.1%	476,224
Sample count: 1,682			

	Est. Pct.	+ / -	Est. Tons
Other Organic	**35.1%**		**12,490,171**
Food	15.7%	0.6%	5,584,506
Leaves & Grass	7.9%	0.7%	2,808,692
Prunings & Trimmings	2.2%	0.4%	790,727
Branches & Stumps	0.1%	0.1%	52,940
Agricultural Crop Residues	0.0%	0.0%	1,765
Manures	0.1%	0.1%	49,291
Textiles	2.1%	0.3%	748,336
Remainder/Composite Organic	6.9%	0.5%	2,453,912
Construction & Demolition	**11.6%**		**4,110,526**
Concrete	1.2%	0.2%	418,600
Asphalt Paving	0.1%	0.1%	49,614
Asphalt Roofing	0.7%	0.2%	252,254
Lumber	4.9%	0.5%	1,746,001
Gypsum Board	1.1%	0.2%	402,784
Rock, Soil & Fines	1.3%	0.3%	461,437
Remainder/Composite C&D	2.2%	0.3%	779,836
Household Hazardous Waste	**0.3%**		**106,497**
Paint	0.1%	0.0%	42,167
Vehicle & Equipment Fluids	0.0%	0.0%	13,596
Used Oil	0.0%	0.0%	1,579
Batteries	0.1%	0.0%	30,929
Remainder/Composite HHW	0.1%	0.0%	18,226
Special Waste	**3.1%**		**1,110,383**
Ash	0.1%	0.0%	21,464
Sewage Solids	0.0%	0.0%	0
Industrial Sludge	0.0%	0.0%	18
Treated Medical Waste	0.0%	0.0%	6,478
Bulky Items	1.8%	0.6%	656,509
Tires	0.4%	0.2%	145,899
Remainder/Composite Special Waste	0.8%	0.3%	280,017
Mixed Residue	**1.8%**	**0.2%**	**637,938**
Totals	**100.0%**		**35,535,453**

Confidence intervals calculated at the 90% confidence level. Percentages for materials may not total 100% due to rounding.

LEGEND FOR ANALYSIS:
- READILY DEGRADABLE
- MODERATELY DEGRADABLE
- SLOWLY DEGRADABLE
- INERT

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Figure H.7 Waste Characterization for Yolo County, California
Source: California Integrated Waste Management Board (CIWMB), Statewide Waste Characterization Study: Results and Final Report, p. 5, 2000

H.3 Calculations to Determine Theoretical Gas Production for Yolo County Bioreactor Landfill

Calculations for the theoretical gas production for the Yolo County Bioreactor landfill are presented herein. The calculations are used to provide the necessary stoichiometric-maximum gas potential for use in the modified Lambda method. Calculations for the modified Lambda method to determine total gas potential are provided following the stoichiometry calculations.

Table H.1 Stoichiometry to Determine Chemical Expression of Yolo County Waste

Step	Component	Type	Dry Weight [lb]	C	H	O	N	S	Ash
				Percent by Weight (dry basis)					
STEP 1	Food	R	22.70	48	6.4	37.6	2.6	0.4	5
	Yard Waste	R	10.20	47.8	6	38	3.4	0.3	4.5
	Wood	M	4.90	49.5	6	42.7	0.2	0.1	1.5
	Paper	M	30.20	43.5	6	44	0.3	0.2	6
	Textiles	M	2.10	55	6.6	31.2	4.6	0.15	2.5
	Plastic	S	8.90	60	7.2	22.8	0	0	10
	Soil	I	12.10	26.3	3	2	0.5	0.2	68
	Glass	I	2.80	0.5	0.1	0.4	0.1	0	98.9
	Metal	I	6.10	4.5	0.6	4.3	0.1	0	90.5
	Total Weight:		**100.00**	R= Readily, M = Moderate, S= Slow, I = Inert					
STEP 2				**Composition [lb]** *(listed in same order of components as Step 1)*					
	Example calculations and notes:			**C**	**H**	**O**	**N**	**S**	**Ash**
	Carbon in food = 22.07 lb x 48%			10.90	1.45	8.54	0.59	0.09	1.14
	Hydrogen in food = 22.07 lb x 6.4%			4.88	0.61	3.88	0.35	0.03	0.46
	Oxygen in food = 22.07 lb x 37.6%			2.43	0.29	2.09	0.01	0.00	0.07
	Nitrogen in food = 22.07 lb x 2.6%			13.14	1.81	13.29	0.09	0.06	1.81
	Sulfur in food = 22.07 lb x 0.4%			1.16	0.14	0.66	0.10	0.00	0.05
	Ash in food = 22.07 lb x 5%			5.34	0.64	2.03	0.00	0.00	0.89
	Total carbon in sample = ∑ carbon (food + … + textiles)			3.18	0.36	0.24	0.06	0.02	8.23
				0.01	0.00	0.01	0.00	0.00	2.77
				0.27	0.04	0.26	0.01	0.00	5.52
	Total, decomposable (R,M,S) portion:			**37.83**	**4.95**	**30.48**	**1.13**	**0.19**	**4.42**
STEP 3	Specific weight = molecular mass			**Specific Weight [lb/mole]**					
	Molar composition of C = 38.62 lb/12.01 lb/mol = 3.21 mol			12.01	1.01	16.00	14.01	32.06	
				Molar Composition [mole]					
STEP				3.150	4.901	1.905	0.081	0.006	
	Sulfur neglected; Composition normalized with respect to N			**Normalized Molar Composition [mole]**					
STEP 5	Parameter *a*, (Normalized Carbon) = (3.215/.006) = 47.16			C, *a*	H, *b*	O, *c*	N, *d*	S, *e*	
				38.91	60.55	23.53	1.00	0.07	
	Chemical expression of waste:			$\mathbf{C_{38.9}H_{60.55}O_{23.53}N}$					

Table H.2 Determination of Maximum Theoretical Gas Production by Stoichiometry

Calculations for Theoretical Gas Production by Stoichiometry for Yolo County Bioreactor

STEP 6

Equation Components

H_20	CH_4	CO_2	NH_3
12.8	20.8	18.1	1.0

Component of H_2O= (4a - b - 2c + 3d)/4 = (4*38.91 – 60.55 - 2*23.53 + 3)/4 = **12.8**

STEP 7

Specific (Molecular) Weight [lb/mole]

C	H	O	N
12.01	1.01	16.00	14.01

Elemental Specific Weight [lb/mole]

H_20	CH_4	CO_2	NH_3
18.02	16.05	44.01	17.04

Ex.: Elemental weight of H_2O = 1.01 lb/mol (2) + 16 lb/mol (1) = 18.02 lb/mol
Elemental weight of $C_aH_bO_cN_d$ = 12.01(38.9) + 1.01 (60.55) + 16 (23.53) + 14.01

Reaction Masses, M

$C_aH_bO_cN_d$ +	H_20 --->	CH_4 +	CO_2 +	NH_3
919.0	229.9	333.3	798.6	17.0

Example: reaction mass of H_2O = (12.8 mol)(18.02 lb/mol) = 229.9 lb
∑ Right Side = 333.3+798.6 + 17 = 1149 ∑ Left Side= 919.0+229.9 =1149

Volume methane produced, $V_{CH4} = (M_{CH4})(W_{degradable}) / [(M_{CaHbOcNd})(W_{CH4})$
Volume methane produced, $V_{CO2} = (M_{CO2})(W_{degradable}) / [(M_{CaHbOcNd})(W_{CO2})$

CH_4 Gas Specific Weight, W_{CH4} [lb/ft³] = 0.0448
CO_2 Gas Specific Weight, W_{CO2} [lb/ft³] = 0.1235

V_{CH4} = [(333.3)(79 lb degradable waste)]/[(919.0)(0.0448 lb/ft3)] = 639.54 ft^3
V_{CO2} = [(798.6)(79 lb degradable waste)]/[(919.0)(0.1235 lb/ft3)] = 555.87 ft^3
Total volume of gas = $V_{CH4} + V_{CO2}$ = 1195.41 ft^3
Proportion of CH_4 of gas = 639.54/1195.41 = 53.4%
Proportion of CO_2 of gas = 555.87/1195.41 = 46.5%

STEP 8

Average moisture content of MSW waste as tipped = 25% (Tchobanoglous 1993)
Wet weight of waste = dry weight x (1 + mc) = 100 lb x (1 + 0.25) = 125 lb
Theoretical gas production by stoichiometry:
= 1195.41 ft^3/125.0 lb = **9.56 ft^3/lb (wet)**

Table H.3 Determination of Theoretical Gas Production by Modified Lambda Method

Step 1: Break out composition into % descriptive modifiers

Inputted				Calculated				
Waste	Type	% MSW	Wet Wt [lb]	V_i	% of Type	Dry weight	W_i [lb]	Total Wt [lb]
Food	R	**23%**	22.7	V_r =	25%	11.21	W_r =	16.24
Yard Waste	R	**10%**	10.2			5.04		
Wood	M	**5%**	4.9	V_m =	43%	2.42	W_m =	18.36
Paper	M	**30%**	30.2			14.91		
Textiles	M	**2%**	2.1			1.04		
Plastic	S	**9%**	8.9	V_s =	13%	4.39	W_s =	4.39
Soil	ND	**18%**		V_n =	19%		W_n =	0.00
Glass	ND	**3%**						
Decomposable Moist Wt=			79 lb	V_t =	100%	39.00	Dry Wt	

V_i = Volume of Type of Waste W_i = Weight of Type of Waste (based on 100 lb sample)

Average moisture content of waste, m.c. = 40%

NOTE: moisture content defined as W_{water}/W_{tot}, unlike geotech definition of W_w/W_{dry}

For 100lb wet sample, weight of water = W_{tot} x m.c. = 0.4 * 100lb = 40 lb

Wt of decomposable fraction - all water contained in waste= 81 - 40 lb = 39 lb

Step 2: Determine Lambda (Half-Life) Factors

Characteristic equation: $V_{ti} = V_i\, e^{-(\lambda it)}$

λ_r = 0.1386

λ_m = 0.0231

λs = 0.0173

To find max theoretical gas production, solve characteristic equation for when V_{ts} = 95% (volume of slowly decomposable material reaches 95% degradation solving, t = 173 yr

Step 3: Select year of interest to determine modifier, V_i (t=173 years)

Readily: V_r@173yrs = (33) $e^{-[(0.1386)(173)]}$ = 1.27E-11

Moderately: V_m@173yrs = (37) $e^{-[(0.0231)(173)]}$ = 6.84E-03

Slowly: V_s@173yrs = (9) $e^{-[(0.0173)(173)]}$ = 4.46E-03

Step 4: Determine % decomposed

Readily: (0.25-(9.56E-12))/0.33 x 100% = 100%

Moderately: (0.43-(7.90E-03))/0.37 x 100% = 98%

Slowly: (0.13-(6.52E-03))/0.09 x 100% = 95%

Step 5: Weight of decomposed weight = % decomposed x dry weight fraction

Readily: 100% x (16.24 lb) 16.24 lb

Moderately: 99% x (18.36 lb) 18.36 lb

Slowly: 95% x (4.39 lb) 4.31 lb

Total decomposed weight= 38.92 lb

Table H.4 Determination of Theoretical Gas Production by Modified Lambda Method **(continued)**

Step 6: Determine gas produced using stoichiometric reaction masses (use as above)
Step 7: Determine volume of gas produced up to time, *t* (t =173 years) V_{CH4} = [(333.3)(38.92)] / [(919.0)(0.0448)] = 315.07 ft^3 V_{CO2} = [(798.6)(38.92)] / [(919.0)(0.1234)] = 274.07 ft^3 Total gas, $V_{total} = V_{CH4} + V_{CO2}$ = 589.14 % CH_4 = 53% %CO_2 = 47% At end of practical biodegradation, theoretical total gas produced = 589.14 ft^3 Gas production at practical end of degradation (t= 137 yr) = 589.14 ft^3/100lb = **5.89 ft^3/lb**

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