United States
Environmental Protection
Agency

EPA-600/R-05/072
June 2005

First-Order Kinetic Gas Generation Model Parameters for Wet Landfills

Courtesy of Dr. Tim Townsend, University of Florida

EPA-600/R-05/072
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by

Debra R. Reinhart
Ayman A. Faour
Civil and Environmental Engineering Department
and Huaxin You
Statistics and Actuarial Science Department
University of Central Florida
PO Box 162445
Orlando, Florida 32816-2445
reinhart@mail.ucf.edu

Contract Number: EP-C-04-023
Work Assignment Number: RN990230.0030

Project Officer: Susan Thorneloe
U.S. Environmental Protection Agency
Air Pollution Prevention and Control Division
Research Triangle Park, NC 27711

U.S. Environmental Protection Agency
Office of Research and Development
Washington, DC 20460

Abstract

Landfill gas is produced as a result of a sequence of physical, chemical, and biological processes occurring within an anaerobic landfill. Landfill operators, energy recovery project owners, regulators, and energy users need to be able to project the volume of gas produced and recovered over time from a landfill. Mathematical and computer models for predicting gas yields are widely available. The U.S. Environmental Protection Agency (U.S. EPA) developed a methodology for determining landfill gas generation based on a first-order degradation model and has provided default values for model input parameters. However, these values are based on data obtained from conventional landfills. Waste stabilization can be enhanced and accelerated so as to occur significantly more rapidly if the landfill is designed and operated as a bioreactor, primarily involving moisture addition. Enhanced waste stabilization will result in increased gas production; therefore, the rate constant (*k*) and methane generation potential (L_0) values will be different from conventional landfills.

The objective of this report is to investigate landfill gas collection from wet cells and estimate first-order gas generation model parameters. The task was accomplished by doing a literature review regarding landfill gas generation and modeling. Case studies of gas collection from wet landfills were identified. Parameters were determined through statistical comparison of predicted and actual gas collection.

The U.S. EPA LandGEM model appears to fit the data well, provided it is preceded by a lag phase of 1.5 yr on average. The model with a lag phase incorporated takes the form

$$Q_{CH_4} = \sum_{i=1}^{n} kM_i \left(L_0 - V_{sto}\right) e^{-k\left(t_i - t_0\right)}$$

where Q_{CH4} is the methane flow rate in cubic meters per year, M_i is the mass of waste accepted in the i^{th} year, V_{st0} is the specific methane volume produced during the lag phase in cubic meters per megagram, an t_0 is the lag time in years.

The terms *k* and L_0, were estimated for a set of landfills with short term waste placement and long term gas collection data. Mean and 95 percent confidence parameter estimates for these data sets were found using mixed-effects model regression followed by bootstrap analysis. The mean values for the V_{st0}, L_0, and *k* were 33 m^3/Mg, 76 m^3/Mg, and 0.28 yr^{-1}, respectively. Parameters were also estimated for three full scale wet landfills where waste was placed over many years. The *k* and L_0 estimated for these landfills were 0.21 yr^{-1} and 115 m^3/Mg; 0.11 yr^{-1} and 95 m^3/Mg; and 0.12 yr^{-1} and 87 m^3/Mg. A conservative set of parameter estimates is suggested based on the upper 95 percent confidence interval parameters as a *k* of 0.3 yr^{-1} and an L_0 of 100 m^3/Mg, with a negligible V_{st0} if the design is optimized and the lag is minimized.

Wet cells were observed to produce more gas at a faster rate than conventional landfills, particularly after they are closed and when more effective leachate recirculation was practiced. To better quantify the parameters for a larger sample of landfill, more data from full-scale landfills are needed with complete data sets that provide descriptions of gas collection systems, gas quality and quantity, waste placement rates, and moisture conditions. It is recommended that a time step of 0.1 yr be used in the model to avoid inaccurate estimation of flow rates, especially when using a *k* value greater than 0.1 yr^{-1}. A LandGEM form based on the cumulative volume of gas generated can be amended to achieve accurate estimates of gas generation.

Foreword

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Sally Gutierrez, Director
National Risk Management Research Laboratory

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Executive Summary

Introduction

Landfill gas is produced as a result of a sequence of physical, chemical, and biological processes occurring within an anaerobic landfill. Landfill operators, energy recovery project owners, regulators, and energy users need to be able to project the volume of gas produced and recovered over time from a landfill. Mathematical and computer models for predicting gas yields are widely available. The U.S. Environmental Protection Agency (U.S. EPA) developed a methodology for determining landfill gas generation based on a first-order degradation model.

The U.S. EPA has provided default values for model input parameters; however, the values are based on data obtained from conventional landfills. Waste stabilization can be enhanced and accelerated so as to occur sig-nificantly more rapidly if the landfill is designed and operated as a bioreactor, primarily involving moisture addition. Enhanced waste stabilization will result in increased gas pro-duction; therefore, the values of the first- order model parameters k (the landfill gas generation rate constant) and L_0 (the methane generation potential) will be different from conventional landfills. The objective of this report is to investigate landfill gas collection from wet cells and estimate first-order gas generation model parameters.

Methodology

Data Sources

Twenty-nine wet landfill sites were considered for analysis, many of them operating parallel dry landfill cells. Sites were divided into two groups. A small number of sites had sufficient wet landfill cell data for analysis to generate k and L_0 parameter estimates.

A second group included full-scale landfills operated as wet cells that did not have enough data for individual modeling and parameter estimates. These data sets represented gas collection over a short period of time and were, therefore, analyzed as a group of single data points.

Parameters Determination

Two approaches were used for model parameter determination; (1) analysis of data collected over most of the gas collection period from waste placed over a very short term, and (2) analysis of data collected over multiple years from waste placed over multiple years. Parameters determined using the two approaches were confirmed through analysis of short-term data from full-scale wet landfills.

Sites with Complete Gas Collection Data and Single Waste Placement

Complete gas collection refers to cells where data collection started immediately after capping of the cells that were filled in a short period of time (less than 1 yr). The specific volumetric data in units of cubic meters per megagram (Mg) were used in the regression analysis. The exponential rise in the gas volume was often seen to be delayed. To account for this delay, different combinations of one or two lag models were fitted from among linear, quadratic, and exponential models. The regression was done using SAS software. The model with the least Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) was selected as the best model.

Mixed-effects model regression was done for the wet cells with single waste placement. Mixed-effects model regression was performed using S-PLUSS 2000 software to find one set of parameters that represented the population of landfills. This study is the first to use mixed-effects in landfill gas modeling. The model fitted is shown in Equation E-1.

$$V_s = V_{st0} + \left(L_0 - V_{st0}\right)\left(1 - e^{-k\left(t-t_0\right)}\right) \qquad \text{E-1}$$

Where:

- V_s = specific methane volume in cubic meters per megagram;
- V_{st0} = specific methane volume produced during the lag phase in cubic meters per megagram;
- L_0 = methane generation potential in cubic meters per megagram;;
- k = landfill gas generation rate constant in reciprocal years; and
- t_0 = lag time in years.

Bootstrap analysis was performed on the best mixed effects model to determine the 95 percent confidence interval. Regression was done on the bootstrap curves to determine the parameters for the confidence interval.

Analysis of Cells with Continuous Flow Data and Multiple Years of Waste Placement

When gas flow rate data were available from sites with multiple years of waste placement, a mathematical equation was developed to describe the gas flow rate as a sum of gas collected from each increment of waste placed over the years. Regression was then performed on the flow rate data to determine the model parameters. A weighting factor based on the standard error of the lag of each wet landfill with single placement and continuous flow data was used to find an average lag period. This lag period was used when modeling landfills with multiple years of waste placement since in those cases it is not possible to determine the lag from the model analysis.

Analysis of Single Data Points

Continuous data from some landfill sites were not available either because the landfill had not been in operation for a long enough period to generate such data or because long-term data were not available. A single data point represents the gas flow rate from a wet landfill cell at a known time after placement of a known waste quantity. Data from 21 full-scale landfills were analyzed. Weighted age for each data point was calculated as the sum of the age of each fraction of waste in a subsequent year multiplied by the mass fraction with respect to the total waste in place. Specific flow rate of these points was plotted versus weighted age and used to check that the parameters determined, though the mixed effects model were reasonable.

Results, Conclusions and Recommendations

The first-order model fit the data analyzed quite well provided it is preceded by a lag phase. A lag phase was observed for sites with continuous data and for some sites with a full-scale single data point as well. An average lag of about 1.5 yr was estimated to occur prior to gas generation for the wet landfills analyzed. A volume based form of the LandGEM model should be used, which takes the form of Equation E-2 when incorporating a lag phase. If it is assumed that 50 percent of gas is methane, the gas flow rate can be calculated using Equation E-3.

$$V = \sum_{i=1}^{n} M_i\left[V_{st)} + \left(L_0 - V_{st0}\right)\left(1 - e^{-k\left(t_i - t_0\right)}\right)\right] \qquad \text{E-2}$$

$$Q = 2\sum_{i=1}^{n} kM_i\left(L_0 - V_{st0}\right)e^{-k\left(t_i - t_0\right)} \qquad \text{E-3}$$

Where:

Q = Gas flow rate in cubic meters per year.

It must be emphasized that the data presented and analyzed in this report are collected gas data, not generated data, and different conclusions may be reached as gas collection efficiency is improved.

When using LandGEM to determine gas flow rates using a k greater than 0.1 yr^{-1}, it is recommended that a time step of 0.1 yr or smaller be used. Differences are not huge, but more accuracy will be obtained.

When the 0.1 yr time step is incorporated, the model can be described by Equation E-4.

$$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=1}^{l} k\left(M_i/10\right)\left(L_0 - V_{st0}\right) e^{-k\left(t_{ij}-t_0\right)} \quad \text{E-4}$$

Where:

i = 1 yr time increment for waste placement;
n = number of years of waste acceptance;
j = 0.1 yr time increment for methane production calculation;
M_i = mass of waste accepted in the i^{th} year in megagrams; and
t_{ij} = age of the j^{th} section of waste mass M_i accepted in the i^{th} year expressed as decimal years (e.g., 3.2 yr).

Table E-1 summarizes the k and L_0 parameter estimates from the study completed herein. For full-scale multiple placement sites SSWMC, Landfill A (name withheld at the request of owner), and CSWMC, the amount of gas produced during the lag phase (1.5 yr), V_{st0}, was assumed to be the same as the values found from the mixed-effects model for the single placement sites (33 m^3/Mg). Although the gas produced in the lag phase (V_{st0}) was often found to be a significant percentage of total gas generation potential, L_0, it is expected that, as wet landfill design is optimized and liquid addition commences shortly after waste placement, gas collection will start earlier, and V_{st0} will be minimized. Therefore, a conservative set of LandGEM parameters, based on the upper 95 percent CI, for wet landfills would be a k of 0.3 yr^{-1}, an L_0 of 100 m^3/Mg, and V_{st0} of zero.

Data from 21 full-scale landfills are plotted in Figure E-1. Several of these older landfills actually did not begin recirculating leachate until just prior to reporting gas collection data, consequently once the waste becomes wet, gas generation would significantly be enhanced. It would appear that early collection flow rates are often significantly lower than would be expected due to delayed leachate recirculation, non-optimal moisture conditions, poor gas capture, and other site-specific reasons. The landfills with weighted age less than 2 yr in Figure E-1 appear to still be experiencing a lag in gas collection.

Table E-1. Summary Table for Parameter Estimation

Method	k (yr^{-1})	L_0 (m^3/Mg)
Single Placement Sites		
Brogborough West	0.39	73
Yolo Full-Scale NE	0.20	83
Yolo Pilot Wet	0.23	88
Multiple Placement Sites		
SSWMC	0.21	115
Landfill A	0.11	95
CSWMC	0.12	87
Mixed-Effects Model		
Mean	0.28	76
Upper 95%	0.28	96
Lower 95%	0.28	54

The "Best Fit Mixed-Effects Model Curve" in Figure E-1 was generated using the set of parameters determined from the mixed-effects model having a k of 0.28 yr^{-1} and an L_0 of 76 m^3/Mg. The lower confidence band has a k of 0.28 yr^{-1} and an L_0 of 54 m^3/Mg. The upper confidence band has a k of 0.28 yr^{-1} and an L_0 of 96 m^3/Mg. The lag was accounted for by shifting the points on the x-axis assuming a lag of 1.5 yr occurred. Since lag is assumed, the model that accounts for a lag was used, with V_{st0} values of 33 m^3/Mg, 0 m^3/Mg, and 77 m^3/Mg for the mean, lower, and upper curves, respectively. Some of the full-scale landfills had very late liquid addition, late capping, or were otherwise dry for a long time before operating as wet landfills. Consequently, lower gas generation from them is observed in con-trast to landfills that would be optimized as wet landfills from their start up.

Wet cells were observed to produce more gas at a faster rate than conventional landfills; particularly after closure and more effective wetting was occurring. Gas generation at dry cells appears to be inhib-

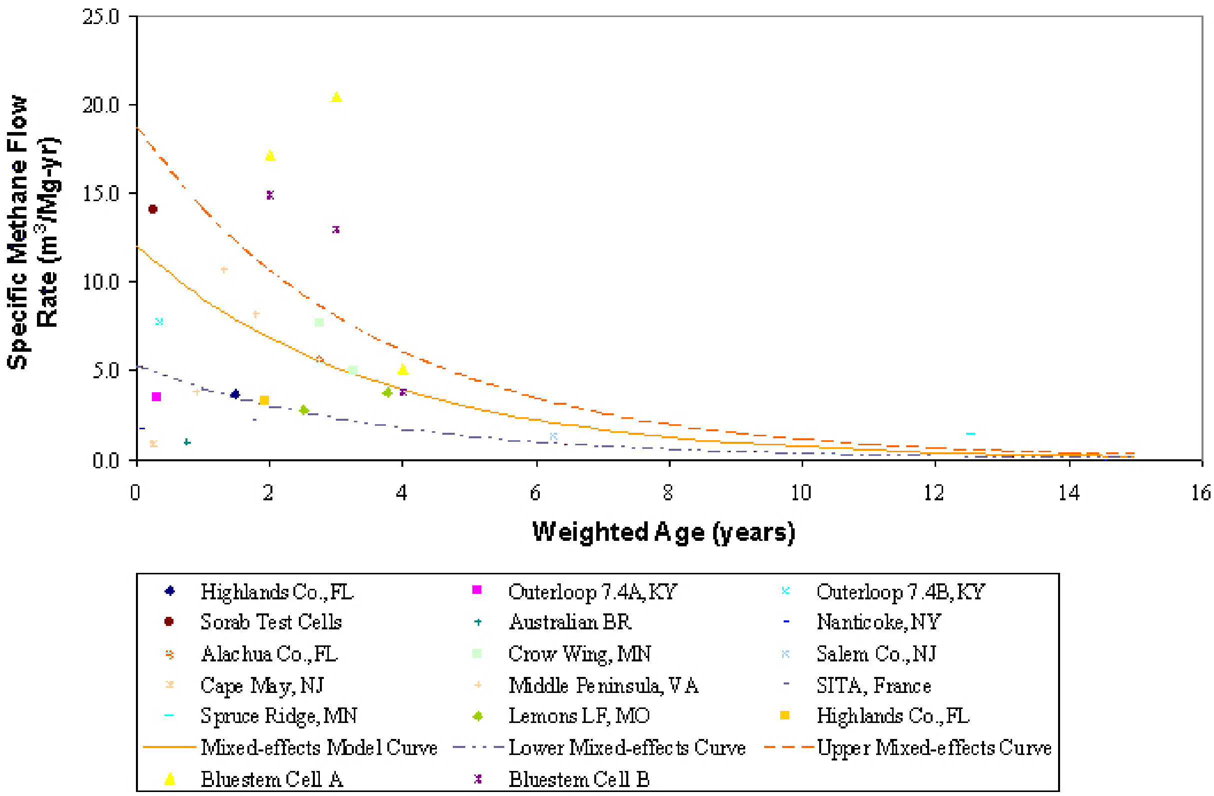

Figure E-1. Single Points and Mixed-Effects Model Curve with 95 Percent Confidence Band

ited, probably due to moisture limitation. Thus, the ultimate methane potential may not be achievable in dry cells.

For similar L_0, a higher k (typical of a wet cell) predicts a higher gas generation rate than a lower k (typical of a dry cell). However for different L_0, a higher k may only suggest a shorter time at which the maximum yield is achieved and does not necessarily predict higher collection rates. Consequently, it is important to evaluate both k and L_0 when modeling gas production.

Model parameters are highly dependent on moisture conditions and capture efficiency. Unfortunately, both of these values are site specific and difficult to quantify. More data from full-scale landfills are needed with complete data sets that provide descriptions of gas collection systems, gas quality and quantity, waste placement rates, and moisture conditions. Moreover, data from the analyzed sites should be updated and incorporated in the study. In the future, long-term gas data should be analyzed since currently very few sites have such data available.

Chapter 1
Introduction

Landfill gas is produced as a result of a sequence of physical, chemical, and biological processes occurring within an anaerobic landfill. The primary components of landfill gas are methane and carbon dioxide, although more than a hundred trace compounds have been identified in landfill gas (Tchobanoglous et al., 1993). Because of the high-energy content of methane and its potent greenhouse gas contributions, there is strong interest in collecting landfill gas and utilizing it as a source of energy. In addition, health and aesthetic considerations dictate collection and treatment of landfill gas.

Landfill operators, energy recovery project owners, regulators, and energy users need to project the volume of gas produced and recovered from a landfill over time. Recovery and energy equipment sizing, project economics, and potential energy uses depend on peak and cumulative landfill-gas production. From a regulatory standpoint, gas generation rates dictate gas control, collection, and destruction requirements to protect the environment and human health.

Gas generation rate is a function of many site-specific variables including waste generation rates, waste composition, climate, nutrient availability, and moisture content of the waste. Mathematical and computer gas-yield prediction models considering these variables are widely available but vary significantly in sophistication. Four parameters must be known if gas production is to be estimated; gas yield per unit weight of waste, the lag time prior to gas production, the shape of the lifetime gas production curve, and the duration of gas production.

In 1996, the U.S. EPA promulgated regulations (amended in 1998) calling for the control of landfill gas emissions. As part of these regulations, the U.S. EPA developed a methodology for determining landfill gas generation based on a first-order degradation model, as seen in Equation 1-1.

$$Q = \sum_{i=1}^{n} 2kL_0 M_i e^{-kt_i}$$

Where:

- Q = total landfill gas emission rate in cubic meters per year;
- n = number of years of waste placement;
- k = landfill gas generation rate constant in reciprocal years;
- L_0 = methane generation potential in cubic meters per megagram;
- M_i = mass of the solid waste section placed in year i in megagrams;
- t_i = age of the waste section placed in year i in years;

Default parameters are provided to estimate gas production in the absence of site-specific data. For regulations under the Clean Air Act (CAA), a k of 0.05 yr^{-1} and an L_0 of 170 m^3/Mg are used, except for landfills in dry areas, where the default k is 0.02 yr^{-1}. These parameter values reflect maximum emissions for determining applicability of New Source Performance Standards (NSPS) and Emission Guidelines (EG). An additional set of default values is provided based on emission factors in the U.S. EPA's AP-42, which are a k of 0.04 yr^{-1} and an L_0 of 100 m^3/Mg, for emission inventories that may more closely reflect actual landfill conditions (U.S. EPA, 1997). The model has been codified in the U.S. EPA's Land-

GEM (Thorneloe et al., 1999).

Waste stabilization can be enhanced and accelerated so as to occur significantly more rapidly if the landfill is designed and operated as a bioreactor, primarily involving moisture addition and leachate recirculation. Enhanced waste stabilization will result in increased gas production; therefore, k and L_0 values will be different from conventional landfills. The definition of a bioreactor landfill varies depending on the source. For example, a Solid Waste Association of North America (SWANA) working group has defined the bioreactor landfill as (Augenstein et al., 1999):

> "…a sanitary landfill operated for the purpose of transforming and stabilizing the readily and moderately decomposable organic waste constituents within 5 to 10 yr following closure by purposeful control to enhance microbiological processes. The bioreactor landfill significantly increases the extent of waste decomposition, conversion rates and process effectiveness over what would otherwise occur within the landfill."

The U.S. EPA defines a bioreactor landfill in recent regulations according to moisture content achieved (45 percent w/w, wet basis) and restricts it to landfills receiving liquids other than leachate. For the purposes of this report, the term, wet landfill, is used rather than bioreactor because of the uncertainty in the amount and impact of operations to enhance waste degradation for each case study.

The objective of this research is to investigate landfill gas emissions from wet cells and to estimate first-order gas generation model parameters. The task was accomplished by doing a pertinent literature review regarding landfill gas collection and modeling. Case studies of gas collection from wet landfills were identified. Parameters were determined through statistical comparison of predicted and actual gas emissions. Most of the sites have not captured all of the generated gas and, therefore, estimated parameters reflect collected not generated gas.

Chapter 2
Literature Review

2.1 Introduction

Landfills are the largest U.S. anthropogenic source of the greenhouse gas methane. An estimated 33 percent of the U.S. global methane emissions is attributed to landfills and open dumps (U.S. EPA, 2002). The explosive nature of methane is a concern. If collected and utilized, methane can help offset the cost associated with landfill gas control (Thorneloe et al., 1999). In March 1996, the U.S. EPA promulgated regulations that require landfills containing 2.5 million Mg of waste and more than 50 Mg/yr of NMOCs to collect and control landfill gas emissions. Consequently, it has become important to understand and predict landfill gas (LFG) emissions.

2.2 Purpose of Modeling Landfill Gas

Landfill gas modeling is needed for sizing landfill gas collection system elements, the number of wells required, the collection pipe size, and gas compressors, for example. Moreover, landfill operators need gas generation information to access the feasibility of a gas energy use project. An alternative to gas modeling is the use of test wells and performance of a test-well program. The cost of the latter method can exceed $100,000 and require three months or more to accomplish (SWANA 1998). These tests provides information regarding gas emissions at specific points in time rather than long-term performance.

2.3 Factors Affecting Methane Generation

There are many factors reported in literature that affect landfill methane generation rates. The most important of these factors are municipal solid waste (MSW) composition and moisture content. Other factors include temperature, leachate pH and alkalinity, particle size and compaction, and nutrients.

2.3.1 MSW Composition

Data compiled by Tchobanoglous, et al. (1993) show that the most significant proportion of the solid waste stream is paper, yard waste, and inorganics, with the amount of yard waste being dependent on the season of the year. Different components of the waste have different methane potentials as well as different biodegradability rates. Table 2-1 shows the physical composition of typical MSW in the United States (Tchobanoglous et al., 1993).

Table 2-1. MSW Composition (% by Weight) for the United States

Component	Range	Typical
Organics		
Food Wastes	6–18	9
Paper	25–40	34
Cardboard	3–10	6
Plastics	4–10	7
Textiles	0–4	2
Rubber	0–2	0.5
Leather	0–2	0.5
Yard Wastes	5–20	18.5
Wood	1–4	2
Inorganics		
Glass	4–12	8
Tin Cans	2–8	6
Aluminum	0–1	0.5
Other Metal	1–4	3
Dirt, Ash, etc.	0–6	3

2.3.2 Moisture

Methanogens require moisture to biodegrade waste, but moisture content in solid waste received at a landfill is generally low—reported to be 25 percent on average for incoming waste by EMCON (1980), 20 percent by Tchobanoglous et al. (1993), and 26 percent by DeWalle et al. (1978). Studies conducted by Ramaswamy (1970), Merz and Stone (1968), and others show that the fraction of methane in gas and the rate of methane production is enhanced by increasing the moisture content, which can be elevated by leachate recirculation, by infiltration of precipitation, or by addition of non-indigenous liquids.

2.3.3 Temperature

Researchers have reported different optimum temperatures for methanogenic activities in landfills, ranging from a low of 30 °C to 41 °C (Hartz et al 1982). If the temperature drops below 20 °C, methane is still produced but at a much lower rate, and growth of methanogenic organisms slows (Gendebien et al., 1992).

2.3.4 Leachate pH and Alkalinity

Methane production is found to be inhibited at pH below 5.5 and alkalinity lower than 1500 mg/l as $CaCO_3$ as reported by Farquhar and Rovers (1973). The optimal pH value is 7.0 to 7.2, although generation proceeds in a pH range of 6.5 to 8.0 (EMCON, 1980).

2.3.5 Particle Size and Compaction

According to DeWalle et al. (1978), shredding increased the gas production rates from landfills, whereas increasing compaction decreased the rates. The same author further predicted that gas production quadrupled when waste particle size decreased by a factor of ten.

2.3.6 Nutrients

Gas production rates are affected by the availability of nitrogen, phosphorous, and potassium in the refuse as reported by Farquhar and Rovers (1973) and by Ramaswamy (1970). Moreover, a carbon to nitrogen ratio of 16 to 19:1 is required to sustain the microbial population (Gendebien et al., 1992). Nutrients may be lost when transported out of the waste if leachate is not recycled.

2.4 Landfill Gas Composition

Landfill gas (LFG) is predominantly methane (45 to 60 percent), with the remaining being carbon dioxide, and 1 to 2 percent other gases or trace organics (Tchobanoglous et al. 1993). A methane range of 40 to 55 percent and 34 to 55 percent for carbon dioxide were reported by EMCON (1980). Furthermore, the U.S. EPA reported in AP-42 that more than one hundred different compounds found in landfill gas (U.S. EPA, 1997).

2.5 Sources of Inefficiency in Landfill Gas Recovery

Camobreco et al. (1999) describes the fate of gas generated from landfills. The first category is gas not collected, which includes the gas produced prior to gas collection system installation, gas produced after discontinuing the gas collection system, and any gas that was not captured by the collection system. The other category is gas that was collected by the gas collection system.

Typically, gas generation starts well before the final landfill cover and gas collection system are installed. The amount of gas not collected before installation of the final cover and gas collection system depends on the lag time of gas generation, if any, and the time between waste placement and installation of final cover. Furthermore, spacing of the wells, gas pressure, and maintenance of the cover can affect the collection efficiency of the gas collection system when in place. Some gas may be lost due to shutting down of the gas collection system when the landfill gas drops below a certain level. Fugitive gas emissions and emissions prior to gas collection system installation contribute to global warming, urban smog and adverse impacts to human health and should be minimized.

2.6 Mathematical Models for Methane Generation

Landfill gas models can be broadly classified into zero-order, first-order, second-order, multiphase, or a combination of orders. The more common models are listed below for reference. Other models are available that are proprietary in nature, and are not addressed here.

2.6.1 Zero-Order Model

In a zero-order model, landfill gas formation is constant over time, and thus no effect of the age of the waste age is incorporated. The zero-order model can be represented by Equation 2-1 (SWANA 1998).

$$Q = \frac{ML_0}{(t_0 - t_f)} \quad \text{for} \quad t_0 < t < t_f \qquad 2\text{-}1$$

Where:

Q = methane generation rate in volume per time;
M = waste in place, mass;
L_0 = methane generation potential in volume per mass;
t = time;
t_0 = lag time; and
t_f = time to end point of generation.

2.6.2 First-Order Model

The effect of age of the waste on gas production is incorporated in the first-order model. For each unit amount of waste, landfill gas generation rates decline exponentially. This model can be represented by Equation 2-2 (SWANA 1998).

$$Q = ML_0 k\, e^{-k(t-t_0)} \qquad 2\text{-}2$$

Where:

k = first-order rate constant in reciprocal time.

2.6.3 Modified First-Order Model

This model assumes that methane generation is initially low and then rises to a maximum before declining exponentially. The equation of this model is represented by Equation 2-3 (Van Zanten and Scheepers 1995).

$$Q = ML_0 \frac{k+s}{s}\left[1 - e^{-s(t-t_0)}\right] k\, e^{-k(t-t_0)} \qquad 2\text{-}3$$

Where:

s = first-order rise phase rate constant in reciprocal time.

2.6.4 Multiphase Model

A multiphase model is based on the first order exponential model (Equation 2-2). It distinguishes different fractions of the waste with different rates of biodegradation. It predicts higher generation rates in the first years and prolonged formation at the end, and it has the form of Equation 2-4 (SWANA 1998).

$$Q = ML_0\left[F_r k_r e^{-k_r(t-t_0)} + F_s k_s e^{-k_s(t-t_0)}\right] \qquad 2\text{-}4$$

Where:

k_r = first-order decay constant for rapidly decomposable waste in reciprocal time;
k_s = first-order decay constant for slowly decomposable waste in reciprocal time;
F_r = fraction of rapidly decomposable waste; and
F_s = fraction of slowly decomposable waste.

2.6.5 Second-Order Model

The second-order model uses a large number of first-order reactions with different rates to describe the complex reactions during degradation of waste (Weekman and Nace, 1970). Being a complex system of different reactions, landfill gas generation can be modeled using the second-order kinetics model.

2.6.6 Scholl Canyon Model

The Scholl Canyon model (EMCON 1980) is the most commonly used model for determining methane gas generation. It assumes that the lag phase is negligible, methane generation peaks immediately, and first-order kinetic rates apply. This model does not account for a lag phase, nor does it consider any limiting factors like moisture. The derivation of this model, for a unit mass placed, is described in Equation 2-5 through Equation 2-9.

$$\frac{-dG}{dt} = kG \qquad 2\text{-}5$$

Where:

G = volume of methane remaining to be produced after time t.

Integrating Equation 2-5 gives

$$G = G_0 e^{-kt} \quad 2\text{-}6$$

$$V = G_0 - G = G_0\left(1 - e^{-kt}\right) \quad 2\text{-}7$$

Where:

G_0 = volume of methane remaining to be produced at $t = 0$; and

V = cumulative methane volume produced prior to time t.

Differentiating Equation 2-7

$$\frac{dV}{dt} = -\frac{dG}{dt} = kG = KG_0 e^{-kt} \quad 2\text{-}8$$

Where:

kG_0 = peak generation rate which occurs at time zero in units of volume per time.

The total generation rate is the summation of the generation rates of the sub masses, Equation 2-9.

$$Q = kG = \sum_{i-1}^{n} r_i k_i G_{0i} e^{-k_i t_i} \quad 2\text{-}9$$

Where:

n = number of years of waste placement;

r_i = fraction of total refuse in submass i;

k_i = gas generation rate constant for submass i, in reciprocal time;

G_{0i} = volume of methane remaining to be produced at $t = 0$ for submass i; and

t_i = age in years of the waste section placed in the i^{th} year.

2.6.7 Triangular Model

This model was used by Halvadakis (1983) and Tchobanoglous et al. (1993). The model assumes a linearly rising first phase followed by a linearly decreasing second phase of generation rates. Tchobanoglous et al. (1993) further assumed a 1 yr lag prior to commencement of methane generation and separate triangular curves for rapidly and slowly decomposable wastes. The total rate is found by summing the rates from the individual components at a given time. The volume of methane generated for the triangular function takes the form

$$L_0 = \frac{1}{2} t_f Q_{sp} \quad 2\text{-}10$$

Where:

Q_{sp} = specific peak rate of methane generation, in volumeper mass-time; and

t_f = time to complete degradation.

Rearranging:

$$Q_{sp} = \frac{2L_0}{t_f} \quad 2\text{-}11$$

2.6.8. Palos Verdes Model

The Palos Verdes Model uses first-order kinetics with the following assumptions:

- Two-phase generation,
- Gas generation rate increases exponentially in the first phase,
- Gas generation rate decreases exponentially in the second phase,
- Equal volume of gas is generated in the first and second phase,
- The peak rate occurs at the transition between the increasing first and decreasing second phases,
- The organic fraction is composed of readily biodegradable, moderately decomposable organics, and refractory organics, and
- The ultimate yield for each organic fraction is based on the fraction's corresponding fraction of the MSW times the ultimate yield of the waste.

The ultimate yield of the organic fraction can be represented by Equation 2-12.

$$L_{0j} = \frac{P_j}{100} L_0 \qquad 2\text{-}12$$

Where:

L_{0j} = methane generation potential of the organic component j;

P_j = component j's percentage of total organic fraction; and,

L_0 = methane generation potential of the whole waste.

Equations 2-13 and 2-14 are used for this model.

$$\frac{dV}{dt} = k_1 V \quad \text{for} \quad 0 < t \le t_{1/2} \left(1^{\text{st}} \ \text{phase}\right) \qquad 2\text{-}13$$

$$\frac{dV}{dt} = -k_2 G \quad \text{for} \quad t > t_{1/2} \left(2^{\text{nd}} \text{phase}\right) \qquad 2\text{-}14$$

Where:

V = volume of gas produced prior to time t;

G = volume of gas remaining to be produced after time t; and

k_1, k_2 = first and second phase gas production rate constants in reciprocal time.

Integrating the first phase equation gives

$$V = V_0 e^{k_1 t} \qquad 2\text{-}15$$

Where:

V_0 = initial gas volume produced.

The first phase equation becomes applicable when gas production reaches 1 percent of the ultimate yield (i.e., V_0 = G_0/100. Integrating the second phase equation, knowing that at $t_{1/2}$, the limit for G is G_0/2, and at time t, the limit is G, gives Equation 2-16.

$$G = \frac{G_0}{2} e^{-k_2\left(t - t_{1/2}\right)} \qquad 2\text{-}16$$

Since $V = G_0 - G$, then

$$V = G_0 \left[1 - \frac{1}{2} e^{-k_2\left(t - t_{1/2}\right)} \right] \qquad 2\text{-}17$$

Drawbacks of the model are that the methane yield of the individual waste categories is not considered and that the assumption that half the gas is produced in each phase may not be accurate.

2.6.9 Sheldon Arleta Model

This model is similar to that of the Palos Verdes Model, as discussed by EMCON (1980). The model assumes a rising exponential curve in the first stage, followed by a decreasing exponential phase in the second phase. The maximum rate occurs when half the gas has been produced; however, it occurs at a time equal to 35 percent of the total generation period. The two categories of waste are considered in this model are (1) readily decomposable with a half-life of 9 yr and total production time of 26 yr, and (2) slowly decomposable with half-life of 16 yr and production time of 103 yr. The assumption that half the gas is generated by the time of the peak rate may not be accurate. Limiting factors are not considered either.

2.6.10 GASFILL Model

The GASFILL model was developed by Findikakis et al. (1988) based on research at the Mountain View Landfill. The model includes a lag phase, a first stage of a rising hyperbolic branch, and a second phase of decreasing exponential branch. It is assumed that carbon dioxide is produced in the same molar quantities as methane and that the waste is composed of readily biodegradable, moderately slowly biodegradable, and slowly biodegradable components. The equations used in the model are

$$Q_j = 0 \quad \text{for} \quad t \le t_{0j} \qquad 2\text{-}18$$

$$Q_j = \coth \alpha_j \left(t_{2j} - t\right) - \coth \alpha_j \left(t_{2j} - t_{0j}\right) \quad \text{for} \quad t_{0j} < t \le t_{1j} \qquad 2\text{-}19$$

$$Q_j = Q_{pj} e^{-\lambda_j (t - t_{1j})} \qquad 2\text{-}20$$

Where:

Q_j = methane generation rate of waste component j in volume per time;

t_{0j} = time when methane gas generation starts for component j;

t_{1j} = time of peak generation for component j;

t_{2j} = time at which the hyperbolic branch of the peak asymptotically approaches infinity;

Q_{pj} = peak methane generation rate in volume per time; and

α_j, λ_j = constants.

Without giving any explanation, Findikakis et al. (1988) used a time of almost 2 yr for the commencement of methane generation for readily biodegradable waste, but a time of less than a year was used for moderately and slowly biodegradable waste.

2.6.11 U.S. EPA LandGEM Model

LandGEM, short for landfill gas emissions model, is software that was developed by the U.S. EPA for quantifying landfill gas emissions. Initial release of the software was in 1991 as described by Thorneloe et al. (1999). LandGEM is based on a first-order decomposition rate equation. The following inputs are required for estimating the amount of gas generated:

- Design capacity of the landfill;
- Amount of waste in place or the annual acceptance rate;
- The methane generation rate constant k and methane generation potential L_0; and
- The number of years of waste acceptance.

Default values for k and L_0 can be used or site-specific values can be developed through field test measurement. The software can be operated under the Windows environment. Graphs and reports of estimated gas emissions can be produced. The gas collection and control requirements of the New Source Performance Standard (NSPS) or Emission Guidelines (EG) for a particular landfill can be estimated using regulatory defaults. The default values in the model provide maximum estimates that would be used for determining the applicability of the gas collection and control requirements to a landfill. For estimation of actual emissions, the default values of the AP-42 are provided in the model, which are based on the U.S. EPA's Compilation of Air Pollutant Emission Factors, AP-42 (U.S. EPA, 1997). Equation 2-21 is used to estimate gas generation from a landfill.

$$Q = 2\sum_{i=1}^{n} k L_0 M_i e^{-k t_i} \qquad 2\text{-}21$$

Where:

Q = total landfill gas emission rate in megagrams per year;

n = number of years of waste placement;

k = methane generation rate constant in reciprocal years;

L_0 = methane generation potential in cubic meters per megagrams of waste;

M_i = mass of the solid waste section placed in year i in megagrams; and

t_i = age in years of the waste section placed in year i.

The following features are provided by the model (Thorneloe et al., 1999):

- Emission rate for methane can be estimated annually over the life of the landfill and for a specific number of years after the landfill is closed;
- Two sets of default values for emissions calculations are incorporated in the model. The first set is for determining the applicability of Federal regulatory requirements (Clean Air Act defaults) and another for developing emission inventories (AP-42 defaults);
- Landfill closure estimates based on the landfill capacity and waste acceptance rate;
- Graphs of methane emissions.

2.6.12 LFGGEN Model

The LFGGEN model, short for landfill gas generation model, was developed at the University of Central Florida (Keely, 1994). The assumptions for this model are a combination of the assumptions made by Findikakis et al. (1988), and Tchobanoglous et al. (1993), which are

- Methanogenesis is preceded by a lag phase;
- The first stage of methanogenesis is represented by a linearly increasing generation rate; and
- The second stage of methanogenesis is represented by first-order kinetics, with an exponentially decreasing generation rate.

The model has some additional features, which are:

- Methods of analysis provided are (1) the theoretical stoichiometric generation of methane and carbon dioxide, (2) biodegradability factors, (3) biochemical methane potential (BMP), (4) and the U.S. EPA Tier 3;
- Biodegradable solid waste is divided into eleven categories;
- Moisture is classified as wet, moderate, and dry; and
- Biodegradability rates are classified as rapid, moderate, and slow. Biodegradability rates are also a function of moisture.

This model includes a time delay t_0 to establish anaerobic conditions, followed by a linear increase to a specific peak rate, Q_{Sp}, that occurs at the end of year, t_P. After the peak, the generation rate decreases exponentially from the peak to a nearly zero rate at the end of the prescribed biodegradation time, t_{99}, which is the time for the gas generation rate to drop to one percent of the peak rate.

The model assumes that the characteristic times t_0, t_P, and t_{99}, vary with the type of waste and moisture condition. The specific peak rate Q_{Sp} is a function of these times and of methane potential as shown in Equation 2-22.

$$Q_{Sp} = L_0 \frac{2k}{k\left(t_p - t_0\right) + 2} \qquad \text{2-22}$$

Where:

Q_{Sp} = specific peak methane rate in cubic meters per year-kilogram;

L_0 = methane generation potential in cubic meters per kilogramg;

t_0 = lag time in years;

t_P = time to peak rate in years; and

k = biodegradation rate constant in reciprocal years.

For the second phase of methanogenesis, the biodegradation constant k is related to the assumed times as shown in Equation 2-23.

$$k = \frac{-\ln 0.01}{t_{99} - t_p} = \frac{4.6052}{t_{99} - t_p} \qquad \text{2-23}$$

Where:

t_{99} = time for gas rate to reach 1 percent of Q_{sp} in years

The equations describing the annual methane production per unit of MSW are

$$Q_{Sj} = 0 \quad 0 < t \le t_{0j} \qquad \text{2-24}$$

$$Q_{Sj} = \frac{Q_{Spj}}{2}\left[\frac{t - t_{0j}}{t_{pj} - t_{0j}} + \frac{(t-1) - t_{0j}}{t_{pj} - t_{0j}}\right] \qquad \text{2-25}$$

$$t_{0j} < t < t_{pj}$$

$$Q_{Sj} = \frac{Q_{Spj}}{2}\left[e^{-k_j\left[t - t_{pj}\right]} + e^{-k_j\left[t-1-t_{pj}\right]}\right] \qquad \text{2-26}$$

$$t_{pj} < t \le t_{99}$$

Where:

Q_{sj} = specific methane generation rate in cubic meters per year-kilogram of component j;

Q_{Spj}= specific peak methane rate in cubic meters per year-kilogram of component j;

t = time from placement of MSW in years; and

j = subscript referring to MSW component j.

Multiplying the annual average methane rate for each

MSW component by the quantity of the waste component and summing gives the total methane produced for a given year and a given lift as seen in Equation 2-27.

$$Q = \sum Q_{Sj} \times M_j \qquad 2\text{-}27$$

Where:

Q = methane generation rate in cubic meters per year;

Q_{Sj} = specific methane generation rate for MSW component j in cubic meters per kilogram-year; and

M_j = mass of MSW component j in kilogram.

2.7 LFG Modeling Studies

In general, gas emission models can predict the gas formation with an accuracy of 50 percent (Oonk et al., 1994). Possible reasons for the inaccuracy suggested by the same author are

- Inaccurate estimates of recovery efficiency;
- Inaccurate data on the amounts of waste and waste composition;
- Variation in landfill gas formation due to the lack of homogeneity of the landfill and presence of inhibitors or nutrients; and
- Inaccuracy of the models used to predict the gas formation

2.7.1 Modeling of Dutch Landfills

Oonk et al. (1994) conducted a gas modeling study based on data collected from nine Dutch landfill gas projects. Data collected included the amount of waste, waste composition, the amount of gas recovered, and some general information on the recovery system and site management. From this information, recovery efficiency was estimated, and landfill gas formation was calculated. The average efficiency considered was around 68 percent.

The approach Oonk et al. (1994) took in their study was to minimize the difference between the calculated gas generation rates and the actual rates to determine the optimal set of gas generation parameters using SAS software for statistical analysis. The error equation used is shown as Equation 2-28.

$$E = \sqrt{\sum_{i=1}^{n} \left(Q_C - Q_{ob}\right)^2} \qquad 2\text{-}28$$

Where:

E = error function;

Q_C = Calculated generation rate in units of volume per time;

Q_{ob} = Observed generation rate in units of volume per time; and

n = number of landfills.

Nine landfills were considered for the study, from which eighteen data points were selected. A maximum of four data points from a particular landfill were used, so that no one landfill dominated the data set. A first-order rate constant of 0.094 yr^{-1} was found. The methane generation potential from organic carbon was assumed to be fixed at 1.87 m^3/kg of organic carbon in the waste. This number was multiplied by the organic carbon content in kilograms per megagrams of waste. Also a generation factor of 0.58, which represents the amount of waste that is degradable, was calculated for the first-order model. Assuming an organic carbon content of 100 kg/Mg of waste and a generation factor of 0.58 as found in the study, the L_0 used would be 108 m^3/Mg.

The study also concluded that the multiphase model best described gas generation at the landfill sites selected with a relative error of 18 percent, followed by the second and first-order models with a relative error of 22 percent, with the zero-order being least reliable with a relative error of 44 percent. The authors acknowledge that the additional parameterization in the multiphase may have contributed to its higher performance.

The approach used by Oonk et al. (1994) is based on a fixed-effects model where the parameters k and L_0 are assumed to be the same for all landfills in the population. Lag phase was not taken into consideration, and it was assumed that the exponential gas generation model started immediately after waste placement. Although a fixed effects model may provide reasonable estimate for the mean of the parameters for the landfills in consideration, it is not appropriate as a predictive tool for other landfills.

2.7.2 Study by SWANA

The Solid Waste Association of North America (SWANA) conducted a study to evaluate gas emission parameters (SWANA, 1998). Landfills with satisfactory data accuracy were chosen according to criteria that included a well-maintained cover, sufficient well density, efficient well configuration, accurate waste receipt history, gas recovery over a significant duration, and accurate methane percentage measurement. Out of twenty-six landfills considered, eighteen were used in the study. Two calibration methods were used; namely, (1) the minimization of arithmetic mean error using the absolute value of the difference and (2) minimization of logarithmic error using the absolute value of the natural log of the ratios. Each of these methods has its advantages and disadvantages (SWANA 1998). It was assumed that methane generation and recovery are the same, and a time interval of 1 yr was used in the optimizations. The models used for calibration were zero- order, first-order, modified first-order, and multiphase first-order models.

For each of the landfills, iterative calculations of the generation rate were run over time for varied parameters through small adjustments in the parameters over a range of numerical values. The sum of the arithmetic differences between projections and experienced methane recoveries for a study landfill were reported as a sum of residuals. The calibrated model was chosen as the model with parameter combinations that gave the minimum arithmetic error.

A similar procedure was used to minimize logarithmic error. The results for the computer runs were scanned visually for optimal results and compared numerically for the lowest minimized error. Values for L_0 for the first-order models under arithmetic optimization were in the range of 54 to 57 m^3/Mg. For logarithmic optimization, the range of L_0 values was 51 to 57 m^3 methane/Mg.

The rate constant, k, was more varied and model dependent. Under arithmetic optimization function, k values ranged from 0.05 to 0.08 yr^{-1}, for the first-order, modified-first order, and multiphase first-order models. Under the logarithmic optimization function, the values of k ranged from 0.03 to 0.06 yr^{-1}. The model parameters obtained from the optimization functions were used to develop generation curves which were plotted against the actual methane recovery data from the 18 landfills, and correlation coefficients were determined for each of the four models. These correlation coefficients were generally higher than 0.9. It was seen from this study, that the values for L_0 are less than suggested by the U.S. EPA of around 100 m^3/yr and k values were close to the U.S. EPA values.

As commented for the study by Oonk et al. (1994), SWANA's study also assumes a fixed-effects model and does not take lag phase into consideration. In addition, minimizing the residual sum of squares (RSS) was done manually without the use of statistical software.

2.7.3 Other Studies

Oonk et al (1994) found an L_0 of 56 m^3/Mg and a k of 0.09 yr^{-1} based on a study of methane yield based on an assumed waste degradable carbon content. An L_0 of 54 m^3/Mg and a k of 0.07 yr^{-1} were found by Augenstein and Pacey (1991) using a commercial model.

2.8 Akaike Information Criterion and Bayesian Information Criterion

For regression problems, a model that performs very well on the training data set may perform poorly on other data sets collected under similar conditions. In order to avoid this problem, many model selection methods have been proposed to perform "honest" model evaluation. Those model methods all attempt to minimize different estimates of prediction error. For linear regression, Mallow's *Cp* has been shown to have very good theoretic properties and empirical results. For regression analysis in general, Akaike information criterion (*AIC*) and Bayesian Information Criterion (*BIC*) are two most popular methods.

AIC is associated with the expected negative log-likelihood of the model evaluated at the sample, adjusted by the number of parameters in the model. Its form is shown in Equation 2-29.

$$AIC = n + n\log(2\pi) + n\log(RSS/n) + 2(df + 1) \quad \text{2-29}$$

Where:

n = Number of observations;
df = Number of parameters in the model;
RSS = Residual sum of squares; and
π = (22/7).

BIC assumes the true model is from a collection of suitable candidate models where each model is assumed to have equal probability of generating the data set. Upon seeing the data values, the posterior probability of each model is calculated. The model with largest posterior probability will be chosen as the optimal model for the data set. Its form is shown in Equation 2-30.

$$BIC = n + n\log(2\pi) + n\log(RSS/n) + \log n(df + 1) \quad \text{2-30}$$

BIC is asymptotically consistent as a selection criterion. That means if the collection of models includes the true model, the probability that *BIC* will select the correct model approaches one as the sample size becomes large. *AIC* does not have the above property. Instead, it tends to choose more complex models as sample size becomes large. For small or moderate samples, *BIC* often chooses models that are too simple, because of its heavy penalty on complexity. Since the data size in this study is usually not small (> 100) and the models used in this study have been proven to be both interpretable and flexible enough to fit the gas generation from a variety of landfills, *BIC* was given preference. The optimal models suggested by *AIC* are also provided for comparison.

The lower the value for *AIC* and *BIC* is, the better is the model. Usually these criteria provide identical optimal models (i.e., a model that has the lowest *AIC* would also have lowest *BIC*).

2.9 Fixed-Effects and Mixed Effects Models

In this report, mixed effects models were selected over fixed effects models. Fixed effects models assume the same non-linear regression model to all the landfills of interest. Moreover, fixed effects models assume that the model parameters k and L_0 are the same for these landfills. Mixed effects models, however, allow the model parameters k and L_0 to change from one landfill to another. We model both k and L_0 as random effects selected from the population of landfills. Experimental results show that mixed effects models explain data much better than fixed effects models.

2.10 Bootstrap Prediction Intervals

A prediction interval for a single future observation is an interval that will, with a specified coverage probability, contain a future observation from the population of interest. In nonlinear mixed effects model inference, it is assumed that the model parameters for future landfills have a certain distribution (e.g., the normal distribution) with its parameters estimated from the landfills studied in this report. Then, a prediction interval may be obtained if the parameters are adequately estimated and the uncertainty in the parameter estimation is suitably assessed. After the mixed effects model is built and its parameters are estimated optimally, a very large collection of resampling pseudo data sets is generated to construct prediction interval for future landfills.

Clearly, such a procedure is dependent on the underlying distribution in that, if the distributional assumption fails, the prediction interval may be seriously inaccurate (i.e., it either is wider than necessary, or does not have the claimed coverage probability). In this study, the distributional assumption is statistically accepted. Moreover, our prediction interval shows that it can cover the majority of single point observations not used in fitting the mixed effects model.

Chapter 3
Methodology

3.1 First-Order Gas Generation Model

LandGEM is the most widely used model for estimating gas emissions from landfills and is also fairly simple to use. The objective of this research is to determine first-order kinetic gas emission parameters for wet landfills and check if LandGEM can adequately estimate gas flow from wet landfills. In the following section, the derivation of the LandGEM is shown.

3.2 Model Derivation

At some point, refuse placed in an anaerobic landfill will degrade, producing methane. With the use of mathematical modeling techniques, predictions concerning the rate and quantity of methane production over the life of the landfill can be made. The LandGEM is based on the first-order gas generation model. Equation 3-1 provides the first-order waste degradation equation.

$$\frac{dM_r}{dt} = -kM_r \qquad 3\text{-}1$$

Where:
- M_r = remaining mass of refuse at time t in megagrams;
- t = time elapsed; and
- k = first-order rate constant in reciprocal years.

When integrated over time, Equation 3-1 becomes

$$M_r = Me^{-kt} \qquad 3\text{-}2$$

Where:
- M = initial mass of degradable refuse in megagrams.

In addition, there is a direct relationship between the refuse mass and the production of methane. This relationship is expressed as

$$V = L_0 M\left(1 - e^{-kt}\right) \qquad 3\text{-}3$$

Where:
- V = cumulative methane generated from beginning of life to time t in cubic meters; and
- L_0 = methane generation potential in cubic meters per megagram.

The rate of methane production per year is obtained by differentiating Equation 3-3 with respect to time to obtain Equation 3-4.

$$Q = kL_0 Me^{-kt} \qquad 3\text{-}4$$

Where:
- Q = methane production rate at time t in cubic meters per year.

In landfill gas, the methane content is approximately 50 percent by volume; therefore, the total gas production rate can be estimated by doubling Q_{CH4} as shown in Equation 3-5.

$$Q_T = 2kL_0 Me^{-kt} \qquad 3\text{-}5$$

Where:
- Q_T = total gas generation rate in cubic meters per megagram-years.

The gas generation rate for a landfill constructed over multiple years can be determined by applying Equation 3-5 over multiple time periods (U.S. EPA's LANDGEM recommends 1 yr increments) and summing the generation rates for each time period (i) for n time periods as shown in Equation 3-6.

$$Q_T = \sum_{i=1}^{n} 2kL_0 M_i e^{-kt_i} \qquad 3\text{-}6$$

Where:

M_i = mass of waste placed in year i in megagrams.

3.3 Model Parameters

3.3.1 Methane Potential

In order to estimate gas generation, the potential for methane production must be determined, usually expressed as the volume of methane per mass of waste. Methane potential can be estimated based on theoretical prediction, laboratory experiments or actual gas production data. At present, there is no method for determining methane potential that is without fault. Table 3-1 provides a summary of total gas (methane and carbon dioxide) potentials reported in the literature.

Table 3-1. Predicted Landfill Gas Potentials[a]

Prediction Basis	Total Gas Generation (m^3/Mg)
"Typical" U.S. municipal solid waste, theoretical estimate	400–520
Weight of organic components by degradability, theoretical estimate	100–310
Anaerobic digestion of refuse with sludge, lab measurement	210–260
Lysimeters operated 1-3 yr	0.2–400
Full-size landfill, projected from existing short-term data	2–400

[a] Sources: Ham and Barlaz (1989); Cooper (1990)

Theoretical predictions are based on the chemical composition of the waste and would give absolute maximum methane potential. In reality, gas generation would never reach this potential due to the inaccessibility of some waste, the inability to biodegrade all organic wastes, and the likely production of other non-methane carbon compounds other than carbon dioxide. Consequently, theoretical methane potential must be adjusted by a biodegradability factor, also based on various assumptions.

A number of researchers have developed an experimental procedure to evaluate the methane potential, called the biochemical methane potential (BMP). The BMP assay is a procedure developed to determine the methane yield of an organic material during its anaerobic decomposition by a mixed microbial flora in a defined medium (ASTM Method E1196-92), and ASTM procedures have been modified for solid waste by Owens and Chynoweth (1992). Researchers have provided BMP values for various waste fractions. With information regarding the component characterization of the waste, L_0 can be calculated from a weighted average of the BMPs.

Actual gas production data have been collected from lysimeters, pilot-scale cells, and full-scale landfills. However, the drawback of utilizing these data is that they reflect gas recovered, not gas generated. Gas recovery efficiency is believed to be far less than 100 percent and depends on many factors such as the presence and integrity of a cover and the type and quality of the gas collection system. The presence of cracks and fissures will reduce collection efficiency. In addition, these studies rarely last sufficiently long to actually reach the point of total gas production. Further, other data necessary, such as waste mass and actual dates of placement, for determining methane potential may not be available.

3.3.2 First-order Rate Constant

The first-order rate constant, k, controls the rate of decline of the first-order model and, consequently, the period of gas generation predicted by the model. As the value of k increases, the duration of gas production declines. For example as k varies from

0.02 to 0.285 yr^{-1}, the time required for 99 percent of the methane to be generated decreases almost fourteen fold. It would be expected that as conditions within a landfill are optimized with respect to waste degradation (i.e., moisture content, temperature, biodegradability of the waste, etc.), k would increase, assuming that L_0 remains the same. However, to date there have been insufficient data to quantify the magnitude of the increase.

3.4 Data Sources

An initial search of the literature produced many potential landfill gas collection data sets for this research. These sites are described in Table 3-2.

Sites were divided into two groups. A small number of sites [Yolo County Pilot Cells, Yolo County full-scale North East (NE) and West Side (WS) cells, Delaware Solid Waste Authority (DSWA) Test Cells, Southern Solid Waste Management Center (SSWMC) in Delaware, Central Solid Waste Management Center (CSWMC) in Delaware, Georgia Tech (GT) Lysimeters, Brogborough Test Cells in the UK, and Landfill A (name withheld at the request of owner)] had sufficient wet cell data for analysis to generate k and L_0 parameter estimates. In some cases, wet and dry landfill cells were operated in parallel, and model parameters were calculated for each. A second group included full-scale landfills operated as wet cells that did not have enough data for individual modeling and parameter estimates. These data sets represented gas collection over a short period of time and were therefore analyzed as a group of single data points, as described in Section 3.5.3.

3.5 Methodology

The following sections describe three approaches for model parameter determination: (1) analysis of data collected over most of the gas collection period from waste placed over a very short term (Yolo County Pilot Cells, Yolo County Full-scale NE and WS cells, DSWA Test Cells, Brogborough test cells, and GT Lysimeters); (2) analysis of data collected over multiple years from waste placed over multiple years (CSWMC, Landfill A, and SSWMC); and (3) analysis of short-term data from full-scale wet landfills.

3.5.1 Analysis of Cells with Complete Gas Collection Data and Single Waste Placement

Complete gas collection refers to cells where data collection started immediately after capping of the cells that were filled in a short period of time (less than 1 yr). Gas flow rates were converted to methane flow rates using the available field methane percentage data. The cumulative volume of methane gas collected was calculated, which was then divided by the mass of waste placed to find the specific cumulative methane volume in units of cubic meters per megagram. Time zero was considered as the time gas collection started. The resulting specific volumetric data were used in the regression analysis.

As it is observed from plotting specific volume versus time, the exponential rise in the gas volume curve is often delayed. This delay is expected since initially conditions may not be optimal for microorganisms to function. To account for this lag phase, different combinations of one or two lag models were tried from among linear, quadratic, and exponential models. That approach gave rise to exponential, linear, or quadratic lag models, or a combination of any two models; for example linear-exponential lag refers to a linear lag model followed by an exponential lag model. These models were chosen for their simplicity. The regression was done using SAS software. Different combinations of these lag models were tried for each landfill, and the model with the least *AIC* and *BIC* was selected as the best model (detailed results shown in Table A-1 of the Appendix). Most of the lag models could be fitted for each data set; however a few did not converge on parameter estimates. Equations 3-7, 3-8, and 3-9 show the different lag models used.

Exponential Model

$$V_s = a\left(e^{k_0 t} - 1\right) \qquad 3\text{-}7$$

Table 3-2. Site Descriptions

Landfill Site	Cover	Data Used	Reference
Alachua County, FL	Not capped	Single data point used	Palumbo (1995)
Binghamton, NY	Capped	Single data point used	NYSERDA (1987)
Brevard County, FL		Data not analyzed[a]	Private communication[b]
Brogborough, UK	Capped	Data analyzed	Private communication
Cape May, NJ		Data not collected	NA[c]
Crow Wing, MN	Capped	2 Single data points used	Private communication
CSWMC, DE	Capped	Data analyzed	Private communication
DSWA Test Cells, DE	Capped	Data analyzed	Private communication
Georgia Tech, GA	Capped	Data analyzed	Pohland el al. (1993)
Highlands County, FL	Partially closed	Single points used	Private communication
Keele Valley, Canada		Data not obtained	NA
Landfill A	Capped	Single data point used	Private communication
Landfill B	Partially closed	Single data point used	Private communication
Lycoming County, PA		Data not collected	Natale et al. (1985)
Middle Peninsula, VA		Single points used	Private communication
Lyndhurst, Australia	Capped	Single data point used	Yuan (1999)
Mill Seal, Monroe County, NY		Data not available	NA
Mountain View, CA		Data not used	Pacey et al. (1987)
Outer Loop, KY	Not capped	Single points used	Private communication
Salem County, NJ	Closed	Single data point used	Knight et al. (2002)
SITA, France	Fine soil cover	Single data point used	Taramini et al. (2003)
SORAB, Sweden	Capped	Single data point used	Lawson et al. (1991)
Spruce Ridge, MN		Data not analyzed[d]	Private communication
SSWMC, DE	Capped	Data analyzed	DSWA
St. Sophie, PQ, Canada		Data not collected	NA
Wijster, The Netherlands	Capped	Single data point used	Oonk and Woelders (1999)
Yolo County full-scale cells (NE and WS), CA	Capped	Data analyzed	Private communication
Yolo County piolt cells, CA	Capped	Data analyzed	Private communication

[a] Waste placement data is not available, and gas collection is only partially practiced.
[b] Private communications are recerenced in the List of References, Chapter 6.
[c] NA = not applicable.
[d] Waste placement is not available, and lechate recirculation started 30 yr after initial waste placement.

Linear Model

$$V_s = a \times t \qquad 3\text{-}8$$

Quadratic Model

$$V_s = b_1 \times t^2 + b_2 \times t \qquad 3\text{-}9$$

Where:

V_s = specific cumulative methane volume generated in units of cubic meters per megagram; and

a, b_1, b_2, and k_0 = model fitting constants.

Equations 3-10 through 3-14 illustrate the use of a linear-quadratic lag model followed by an exponential rise to a maximum gas generation model.

For $0 < t < d_0$ then

$$V_s = a \times t \qquad 3\text{-}10$$

$$V_{sd0} = a \times d_0 \qquad 3\text{-}11$$

For $d_0 < t < t_0$ then

$$V_s = b_1 \left(t - d_0\right)^2 + b_2 (t - d_0) + V_{sd0} \qquad 3\text{-}12$$

$$V_{st0} = b_1 \left(t_0 - d_0\right)^2 + b_2 \left(t_0 - d_0\right) + V_{sd0} \qquad 3\text{-}13$$

For $t > t_0$ then

$$V_s = \left(L_0 - V_{st0}\right)\left[1 - e^{-k\left(t - t_0\right)}\right] + V_{st0} \qquad 3\text{-}14$$

Where:

d_0 = end time of lag phase 1;

t_0 = end time of lag phase 2; and

V_{sd0} = cumulative volume of methane collected at the end of lag phase 1 time d_0

V_{st0} = cumulative volume of methane collected at the end of lag phase 2 time t_0.

Regressing data as described above provides estimates for d_0, t_0, V_{sd0}, V_{st0}, k, and L_0.

This regression approach is illustrated for the Yolo County pilot wet cell data below. After running all the different model combinations for a lag followed by the integrated form of LandGEM, the best lag model was found to be the exponential-quadratic model. The first break point was calculated to occur at 202 days and the second at 798 days. Gas collected at each point was 2.2 m^3/Mg and 55.6 m^3/Mg, respectively. Estimates for k and L_0 were 0.23 yr^{-1} and 88 m^3/Mg. The fitting parameters were 0.207 m^3/Mg and 0.0122 day^{-1} for the coefficient and rate of the exponential model, respectively. The coefficients of the quadratic model were -4×10^{-5} m^3/Mg-day^2 and 0.113 m^3/Mg-day. The *BIC* for the model was 826.

After doing the above regression procedure for all data sets with single waste placement, mixed-effects model regression was done for the wet cells taking into consideration only the data after the lag time, t_0, estimated in the best fit model for each cell. The specific volume at the time of beginning of the exponential model at time t_0 was noted as V_{st0}. Mixed-effects model regression was performed using S-PLUSS 2000 software to find one set of parameters that represented the population of landfills. The three parameters in the mixed-effects model are k, L_0, and V_{st0}. When using a mixed-effects model, it can be determined which parameters are fixed (i.e., the same for all landfills in the population) and which parameters are random (i.e., vary from one landfill to another within the population) based on the model selection criteria *AIC* and *BIC*. Mixed-effects models have the advantage over fixed-effects models by being better predictive models. In previous studies, only fixed effects were accounted for. This study is the first to use mixed-effects in landfill gas modeling. The time of the start of the exponential rise to a maximum model (i.e., lag time t_0) can also be, in theory, incorporated into the model as one of the parameters, but that is not computationally practical since the model may be too complex and the software may fail to find parameter estimates. Also, with only four wet landfill data sets available, having four parameters to estimate in a mixed-effects model can be prohibitive. The model fitted is shown in Equation 3-15.

$$V_s = V_{st0} + \left(L_0 - V_{st0}\right)\left[1 - e^{-k\left(t-t_0\right)}\right] \qquad 3\text{-}15$$

Two data sets were considered for parameter estimates. The first data set included four landfills, namely, Brogborough wet cell, Yolo County NE wet cell, Yolo County pilot wet cell, and Georgia Tech wet lysimeters. The second data set is the same except that the Georgia Tech wet lysimeter is not included since it may not be representative of a full-scale landfill. It's ultimate yield was achieved in significantly less time than a full-scale cell, resulting in a very high estimate for *k*. Also, the Yolo County West Side Cell was excluded from both data sets, since insufficient data exist to give a good estimate of the parameters. Results from both data sets are presented in this report; however, only the results from the data set excluding Georgia Tech wet lysimeters will be considered for further discussion.

Multiple models were regressed by fixing one or more parameters and specifying the others as random giving the following models: k fixed, L_0 and V_{st0} random; L_0 fixed, k and V_{st0} random; V_{st0} fixed, k and L_0 random; k and L_0 fixed, V_{st0} random; k and V_{st0} fixed, L_0 random; k and L_0 fixed, V_{st0} random; all random parameters; and all fixed parameters. The best model was selected by examining the *AIC* and *BIC* values for each model.

Bootstrap analysis was performed on the best mixed effects model to determine the 95 percent confidence interval. Regression was done on the bootstrap curves to determine the parameters for the confidence interval.

3.5.2 Analysis of Cells with Continuous Flow Data and Multiple Years of Waste Placement

When gas flow rate data were available from sites with multiple years of waste placement, a mathematical equation was developed to describe the gas flow rate as a sum of gas collected from each increment of waste placed over the years. The mathematical equation takes into account the amount of waste placed each year as well as the age of each fraction of waste at a particular point in time. It then sums up the flow rates from each portion of waste to get the total flow rate. Since gas data immediately after waste placement are not available for these cells, lag periods as well as the specific volume of gas produced in the lag phase, V_{st0}, cannot be estimated statistically. A lag phase of 1.5 yr was assumed to precede exponential gas generation, which is the weighted average of the lag periods of the single placement wet landfills. Data were then regressed and best-fit parameters were found. V_{st0} found from the mixed-effects model for the single placement sites with complete gas collection data was used to estimate L_0 by adding V_{st0} to $(L_0 - V_{st0})$.

An example of this approach is illustrated below for Landfill A, which accepted waste for 17 yr. Regression was done using flow rate data rather than cumulative volume, since initial gas collection data were not available. Equation 3-16 was used for the first year immediately after placement of the last portion of waste. The waste fractions placed during the last 2 yr are not accounted for in this equation since they are considered to be in the lag phase, and their gas production contribution is minimal compared to the

$$\begin{aligned} Q = {} & M_1(L_o - V_{sto})ke^{-k(t-1.5)} + M_2(L_o - V_{sto})ke^{-k(t-1-1.5)} + M_3(L_o - V_{sto})ke^{-k(t-2-1.5)} + \\ & M_4(L_o - V_{sto})ke^{-k(t-3-1.5)} + M_5(L_o - V_{sto})ke^{-k(t-4-1.5)} + M_6(L_o - V_{sto})ke^{-k(t-5-1.5)} + \\ & M_7(L_o - V_{sto})ke^{-k(t-6-1.5)} + M_8(L_o - V_{sto})ke^{-k(t-7-1.5)} + M_9(L_o - V_{sto})ke^{-k(t-8-1.5)} + \\ & M_{10}(L_o - V_{sto})kbe^{-k(t-9-1.5)} + M_{11}(L_o - V_{sto})ke^{-k(t-10-1.5)} + M_{12}(L_o - V_{sto})e^{-k(t-11-1.5)} + \\ & M_{13}(L_o - V_{sto})ke^{-k(t-12-1.5)} + M_{14}(L_o - V_{sto})ke^{-k(t-13-1.5)} + M_{15}(L_o - V_{sto})ke^{-k(t-14-1.5)} \end{aligned} \qquad 3-16$$

$$\begin{aligned}Q = {} & M_1(L_o - V_{sto})ke^{-k(t-1.5)} + M_2(L_o - V_{sto})ke^{-k(t-1-1.5)} + M_3(L_o - V_{sto})ke^{-k(t-2-1.5)} + \\ & M_4(L_o - V_{sto})ke^{-k(t-3-1.5)} + M_5(L_o - V_{sto})ke^{-k(t-4-1.5)} + M_6(L_o - V_{sto})ke^{-k(t-5-1.5)} + \\ & M_7(L_o - V_{sto})ke^{-k(t-6-1.5)} + M_8(L_o - V_{sto})ke^{-k(t-7-1.5)} + M_9(L_o - V_{sto})ke^{-k(t-8-1.5)} + \\ & M_{10}(L_o - V_{sto})kbe^{-k(t-9-1.5)} + M_{11}(L_o - V_{sto})ke^{-k(t-10-1.5)} + M_{12}(L_o - V_{sto})e^{-k(t-11-1.5)} + \\ & M_{13}(L_o - V_{sto})ke^{-k(t-12-1.5)} + M_{14}(L_o - V_{sto})ke^{-k(t-13-1.5)} + M_{15}(L_o - V_{sto})ke^{-k(t-14-1.5)} + \\ & M_{16}(L_o - V_{sto})ke^{-k(t-14-1.5)} + M_{17}(L_o - V_{sto})ke^{-k(t-15-1.5)} + M_{18}(L_o - V_{sto})ke^{-k(t-16-1.5)}\end{aligned} \quad 3-17$$

overall gas produced from waste fractions that have passed the lag phase.

For a time of 1 yr following waste placement, another component was added to Equation 3-16 to account for the waste placed 2 yr prior to the year in consideration, which had also passed its lag phase. Similarly after 2 yr, another part was added and the equation, after all waste fractions are beyond lag phase, is shown in Equation 3-17, where
M_1, M_2, …,M_{18} are the mass in megagrams of waste placed in the subsequent years.

The numbers subtracted from t are the age of waste placed in a year relative to the initial waste placement, and the “1.5” subtracted is the weighted lag period. Values of k and $(L_0\text{-}V_{st0})$ of 0.107 yr^{-1} and 62 m^3/Mg were found, respectively.

3.5.3 Analysis of Single Data Points

Continuous data from some landfill sites were not available, either because the landfill had not been in operation for a long enough period to generate such data or because long-term data were not available in the literature. A single data point represents the gas flow rate from a wet landfill cell at a known time after placement of a known waste quantity. If waste is placed over a short period of time (less than 1 yr), the time for the data point was simply the time period between waste placement and the data point. However, if waste was placed over multiple years, this approach is not valid because the flow rate at the data point is the summation of flow rates from waste increments of different ages. To account for the difference in waste age, the weighted age was calculated for each data point. Weighted age was calculated as the sum of the age of each fraction of waste in a subsequent year multiplied by the mass fraction with respect to the total waste in place. An illustration is provided in Table 3-3 for a data point in year 2003. It can be seen that even though the initial waste placed is 8 yr old, the weighted age is 5.7 yr.

Table 3-3. Weighted Age Calculation Illustration

Year	Waste Placed Mass (Mg)	Mass Fraction	Age (yr)	Mass Fraction × Age
1995	1000	0.1	8	0.8
1996	2000	0.2	7	1.4
1997	2000	0.2	6	1.2
1998	3000	0.3	5	1.5
1999	2000	0.2	4	0.8
Total	10,000		**Sum**	5.7

When methane percentage for a data point was not given, 50 percent was assumed. When annual waste placement data were not available, it was assumed that the annual acceptance rate of waste was constant. Flow rates were normalized with respect to the amount of waste in place by finding the specific methane flow rates. To calculate specific methane flow rates, the methane flow rate was divided by the total waste placed as shown by Equations 3-19.

$$Q = \sum_{i=1}^{n} M_i L_0 k e^{-kt_i} \quad 3\text{-}18$$

Assuming $M_T = M_1 + M_2 + \ldots.. + M_i$, then

$$Q_S = \frac{Q}{M_T} = \frac{L_0 k}{M_T} \sum_{i=1}^{n} M_i e^{-kt_i} \quad 3\text{-}19$$

The specific methane flow rates for the different sites were then plotted versus weighted age. The upper and lower 95 percent confidence curves were plotted for comparison.

3.6 Weighted Lag Period Determination

Different lag periods were calculated for each wet landfill. A weighting factor based on the standard error of the lag of each wet landfill was used to find an average lag period. This lag period is used when modeling landfills with multiple years of waste placement since in those cases it is not possible to determine the lag from the model analysis as discussed in section 3.5.2. Also, it gives a good estimate of the duration of the lag period in wet landfills in general. The weighing factor was computed as shown in Equation 3-20 and Equation 3-21, based on Hedges and Olkin (1985).

$$W_i = \frac{1}{\text{var}(t_0)} \qquad \text{3-20}$$

$$\hat{t}_0 = \frac{\sum_{i=1}^{n} W_i t_{0i}}{\sum_{i=1}^{n} W_i} \qquad \text{3-21}$$

Where:

i = number of sites used for determining weighted lag;

t_0 = lag time for individual sites;

W = weighing factor for each site lag time; and

$\hat{t}_0$ = weighted lag time.

Chapter 4: Results And Discussion

4.1 Introduction

This chapter will present issues related to using LandGEM, development of model parameters, and comparison of model to full-scale wet landfill gas production.

4.2 Model Problems

The exponential model used in LandGEM has advantages associated with its simplicity and limited number of parameters. Also, the model can be modified to include an initial lag phase (SWANA, 1998). However, because of its simplicity, there are several problems associated with its application to full-scale landfills as discussed below.

4.2.1 Effect of Time Increment on Ultimate Yield

The LandGEM model is normally applied assuming waste placement occurs in 1 yr increments and gas generation from waste is constant over a 1 yr period. Thus, the amount of waste placed over the full year is used, and the resulting gas emission rate is taken to be the same during the entire year for which it was calculated. This assumption is not very accurate, however, because the waste placed at the beginning of the year and waste placed at the end of the year will be dealt with as if it is of the same age. Moreover, the gas flow rate from the waste varies with time over a year period due to the aging of the portions of waste placed at different times through out the year. With multiple years of waste placement in a landfill and a 1 yr time increment, it has been observed that as k increases, cumulative specific volume, $(\Sigma Q \Delta t)/M$, as calculated by Equation 3-6 approaches a value less than L_0, the ultimate yield, as t approaches infinity for a Δt of 1 yr. This phenomenon is illustrated in Figure 4-1. Note that an L_0 of 100 m^3/Mg and 25 yr of waste placement were used for demonstration.

However, when the time step was changed from 1 yr to 0.1 yr, the cumulative specific volume is seen in Figure 4-2 to converge at 2500 m^3/Mg for different values of k, as would be expected. Because of the rapid change in gas production over time at high k values, a 1 yr increment no longer approximates the smooth exponential curve adequately. However, if the cumulative volume equation is used (Equation 3-3), this problem is not encountered, as shown in Figure 4-3.

As an example of the difference in flow rate calculated using a 1 yr time increment versus using a 0.1 yr increment, the following placement scenario is used: a landfill with 8 yr of waste placement (1000 Mg, 1250 Mg, 1500 Mg, 1750 Mg, 2000 Mg, 2250 Mg, 2500 Mg, and 2750 Mg for each consecutive year). For a k of 0.4 yr^{-1} and an L_0 of 100 m^3/Mg, the difference in calculated flow rate using the two time increments would be 15.9 percent (i.e., using a 1 yr time increment would be overestimating gas generation by 15.9 percent).

4.2.2 Rate Constant for Different L_0 Values

The ultimate gas potential, or yield, should be a function only of waste characteristics independent of landfill conditions. However, in reality, at practical time scales, the yield will be impacted by moisture conditions and the availability of the waste to microorganisms (the effects of isolation by plastic bags, for example). In addition, landfill gas data will represent collected gas, not generated gas. The determination of

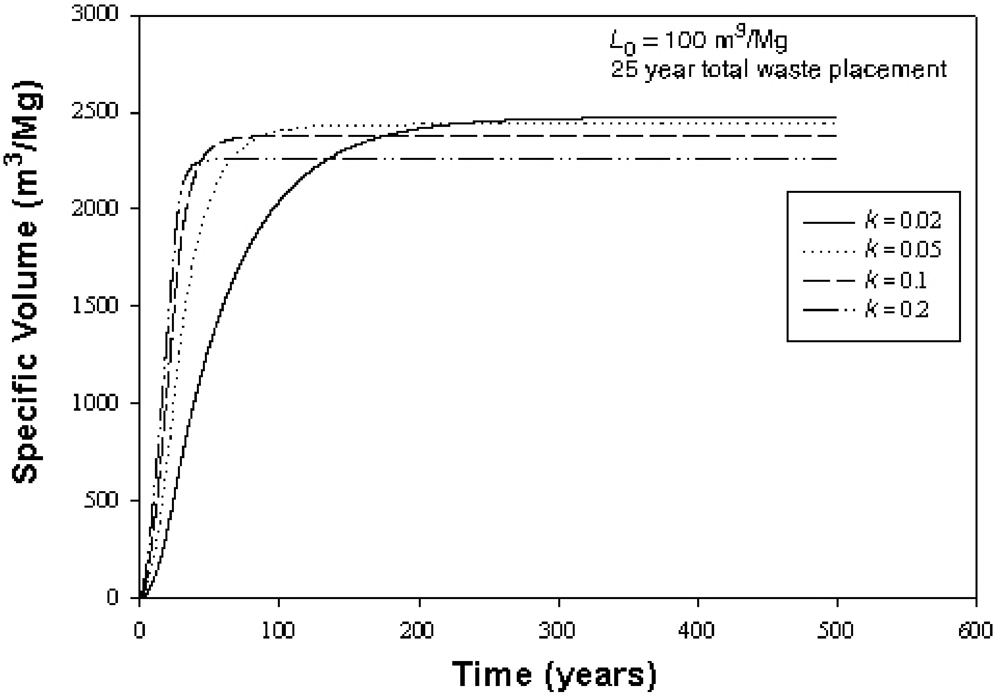

Figure 4-1. Specific Volume for 1 Yr Time Increment Calculated Using Flow Rate Equation.

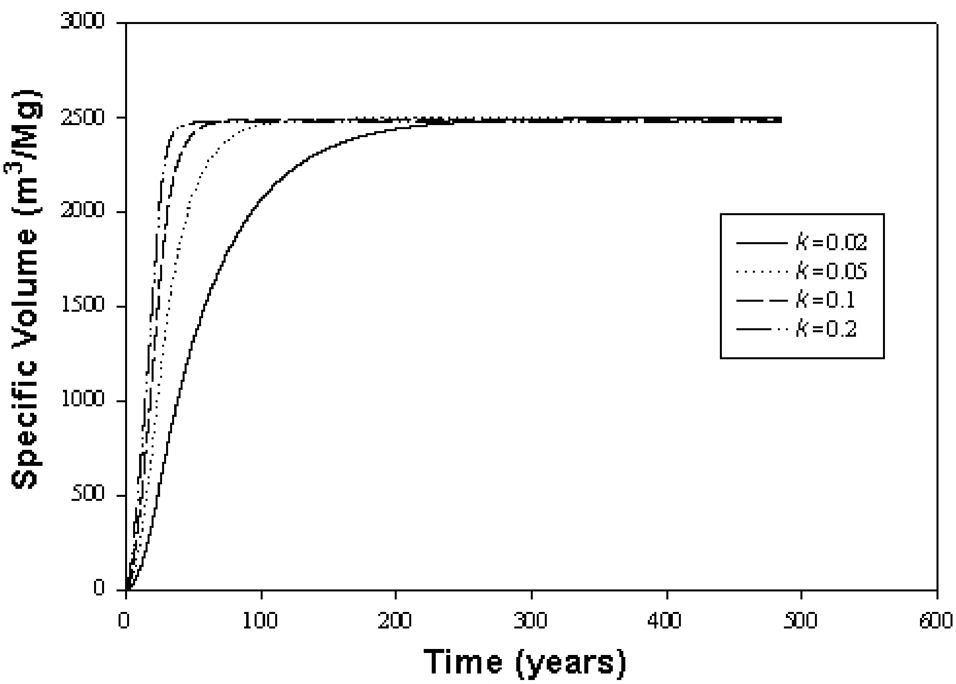

Figure 4-2. Specific Volume for 0.1 Yr Time Increment Calculated Using Flow Rate Equation.

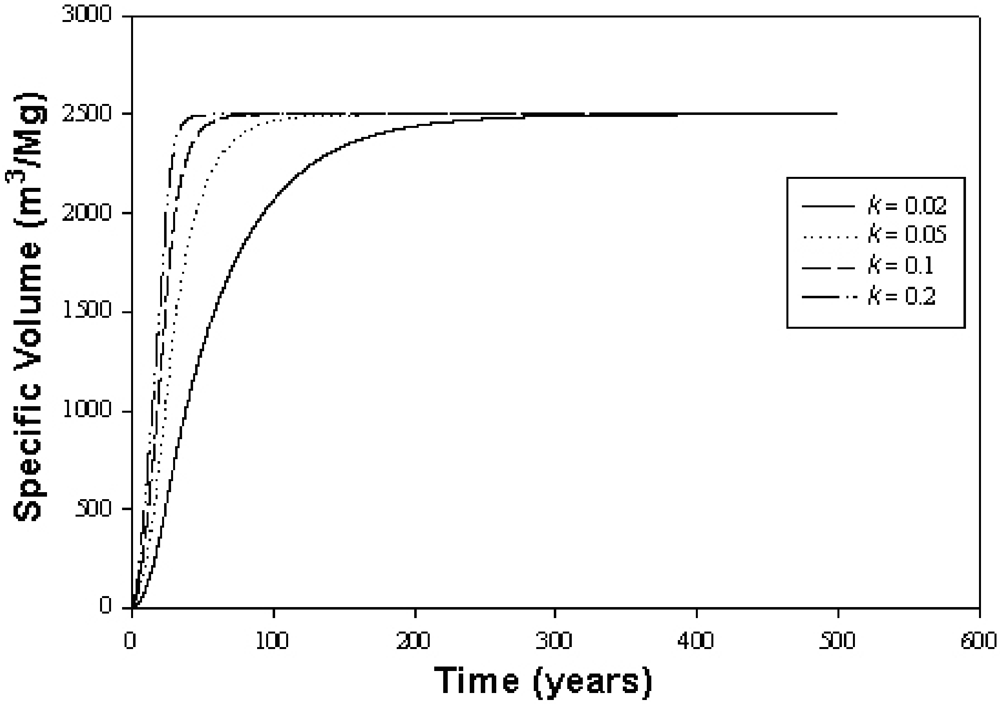

Figure 4-3. Specific Volume for 1-Year Time Increment Calculated Using Cumulative Volume Equation.

the first-order rate constant, k, is generally assumed to be independent of L_0. The exercise described below illustrates that k may indeed be impacted by the value of L_0.

Two hypothetical data sets were examined. Data Set 1 has a k of 0.5 yr^{-1} and an L_0 of 40 m^3/Mg, and Data Set 2 has a k of 0.2 yr^{-1} and an L_0 of 100 m^3/Mg. It can be seen in Figure 4-4 that Data Set 2, although having higher flow rates than Set 1 at any point in time, has a lower k value. In the field, wet landfills would be expected to achieve higher methane yields as compared to dry landfills due to optimal conditions. The lower ultimate achievable yield for dry landfills may be attained in a shorter amount of time than the wet landfill, and a higher k value would more accurately predict gas generation when applying the first-order gas generation model. This higher value does not actually reflect the efficiency of the microorganisms responsible for waste degradation, but rather is a mathematical anomaly of the model.

4.3 Results of Single Placement Sites with Continuous Gas Collection Data

4.3.1 Parameters Results

Table 4-1 provides a summary of the lag type, lag time t_0, the gas generation rate constant k, and the methane generation potential L_0 as determined by the best fit model for each data set. The standard deviations of the parameter estimates are shown in parenthesis. All the models tried for the Yolo County Pilot Dry Cell had an unreasonably high standard error for the lag time.

4.3.2 Weighted Lag for Single Waste Placement Landfills with Continuous Gas Collection Data

Table 4-2 summarizes the different parameters involved in determining the weighted lag for the wet landfills with single waste placement and complete gas collection data. Even though results from Yolo County WS cell were not used in estimating k and L_0

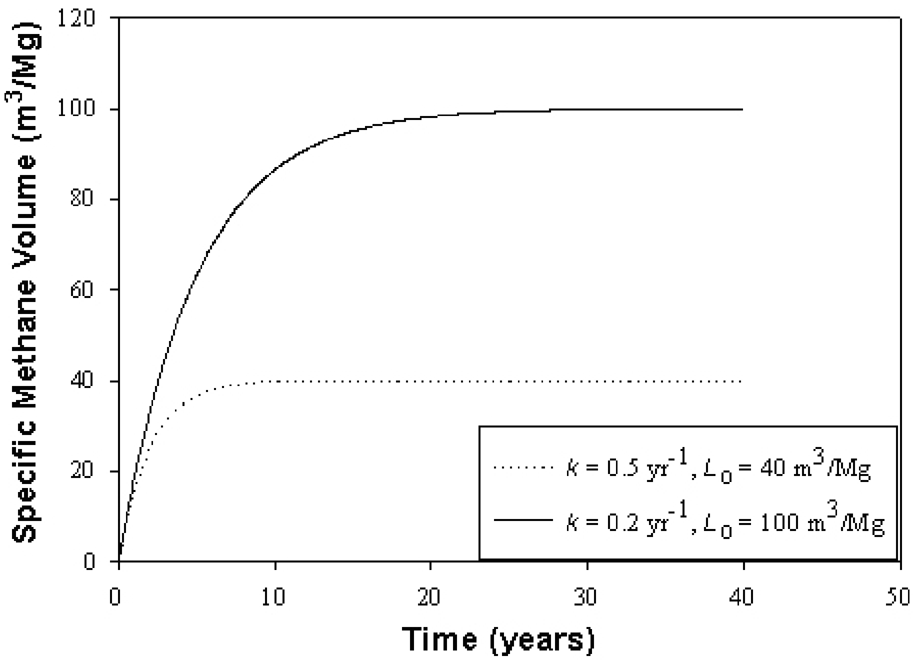

Figure 4-4. Gas Volume vs Time for Different L_0 and k Values.

Table 4-1. Best Model Parameters for Single Placement Landfills

Landfill	Lag Model	t_0 (yr)	k (yr^{-1})	L_0 (m^3/Mg)
Dry				
Brogborough Dry 1	Exp-Quad	5.6 (0.028)[a]	0.072 (0.0027)	144 (4)
Brogborough Dry 2	Lin-Quad	5.7 (0.031)	0.21 (0.019)	59 (3)
Yolo Pilot Dry	Quad-Lin	1.2 ($6.8\times10^{+5}$)	2.5 (0.045)	28 (0.04)
Georgia Tech Dry	Quad-Exp	3.4 (0.0072)	3.0 (0.20)	29 (0.4)
Wet				
Brogborough Wet	Exp-Exp	6.6 (0.081)	0.39 (0.0091)	73 (0.4)
Yolo Full-Scale NE	Lin-Lin	1.0 (0.0069)	0.20 (0.023)	83 (8)
Yolo Full-Scale West	Lin-Exp	1.3 (0.0086)	2.2 (0.65)	9 (1)
Yolo Pilot Wet	Exp-Quad	2.2 (0.0070)	0.23 (0.0051)	88 (0.4)
Georgia Tech Wet	Exp	2.5 (0.022)	1.7 (0.058)	85 (0.7)

[a] The numbers in parentheses are the standard deviations.

Table 4-2. Weighted Lag Estimation

Landfill	t_0 (days)	Stde[a] t_0	Var[b] t_0	$W_i/\Sigma W_i$[c]	$W_i t_0/\Sigma W_i$
Yolo NE	347	2.5	6.4	0.37	128
Yolo WS	487	3.1	9.9	0.24	116
Yolo Pilot West	798	2.6	6.5	0.36	286
Georgia Tech Wet	898	8.1	65.9	0.04	32
				Weighted Lag	**562 days ~ 1.5 years**

[a] Stde is standard error.
[b] Var is variance.
[c] W_i is the weighting factor.

Table 4-3. Results for the Best Mixed-Effects Models

Landfills	Fixed	Random	k (yr^{-1})	L_0 (m^3/Mg)	V_{St0} (m^3/Mg)
4	None	V_{St0}, k, L_0	0.65 (0.32, 0.63)[a]	81 (4, 7)	30 (10, 19)
3	k	V_{St0}, L_0	0.28 (0.0037)[b]	76 (6, 10)	33 (12, 21)

[a] Numbers in parentheses are (mean standard error, random effect standard error).
[b] Standard error only.

since the data were not collected for a long enough period, regression analysis still showed that the lag phase had already passed and provided a reasonable estimate of the lag time. Thus lag time from this site was incorporated into determining the weighed lag period. Brogborough Wet Cell had an unreasonable lag time (5.6 yr) and was not incorporated into the weighted lag estimation.

4.3.3 Mixed-Effects Model Results

Table 4-3 summarizes the results for the mixed-effects model regression performed using the four landfills data set (Brogborough wet cell, Yolo County NE wet cell, Yolo County pilot wet cell, and Georgia Tech wet lysimeters) and the three landfills data set (Brogborough wet cell, Yolo County NE wet cell, and Yolo County pilot wet cell). Detailed results for all the mixed-effects models tried are presented in Table A-3 of the Appendix. It was found that the fixed-effects models performed the poorest, having the highest *AIC* and *BIC* values. It should be noted that, for the three landfill data set, the model chosen for further analysis was the one with a random V_{st0} and L_0, which had the second best fit. The best model was not used since it adds to the complexity of the model while having comparable performance in terms of *AIC* and *BIC* to the model used.

The model for the three landfill data set with k, L_0, and V_{st0} of 0.28 yr^{-1}, 76 m^3/Mg, and 33 m^3/Mg, respectively, was selected as the best model and will be used for further analysis and for performing the bootstrap analysis to find the confidence intervals for the parameters. Since k was a fixed effect, only the standard error of the fixed effect is presented (i.e., 0.0037).

Bootstrap analysis was performed to estimate the upper and lower 95 percent confidence interval. The upper and lower parameters estimates were found by regression of the confidence interval data. The results are shown in Table 4-4.

Table 4-4. Bootstrap Analysis Results

Term	k (yr^{-1})	V_{st0} (m^3/Mg)	L_0 (m^3/Mg)
Mean	0.28	33	76
Lower 95%	0.28	0	54
Upper 95%	0.28	77	96

4.4 Results of Multiple Placement Sites with Continuous Gas Collection Data

Table 4-5 summarizes the k and (L_0 - V_{st0}) values for data sets with multiple years of waste placement and continuous gas collection. For these sites, a 1.5 yr lag period was assumed as discussed in Section 3.5.2.

4.5 Discussion of Results for Single Placement Sites with Continuous Flow Data

4.5.1 Brogborough Test Cells

Six MSW landfill test cells were constructed at the Brogborough landfill in Bedfordshire, UK. The cells considered in this study are the control cell (Cell 1 with 14,270 Mg MSW), the higher density control cell (Cell 2 with 13,980 Mg MSW), and the water and leachate injection cell (Cell 3 with 15,130 Mg MSW). The Brogborough project report notes that after placement of waste, densities of both Cells 1 and 2 were almost identical, so they served as replicate control cells. Waste placement started in March 1987 and took about 6 weeks to complete. The planned height was 10 m, but due to a need for additional space for waste disposal, the height was increased to 20 m in the beginning of 1988. The clay cap was removed, and four more lifts of waste were placed between July and October 1988. From March to May 1989 a 2 m clay cap was placed. In August 1989, new gas collection wells were installed, and gas monitoring started soon afterwards. In January 1990, passive gas collection began, and the main gas collection system was abandoned. A new gas meter was tried in April 1990. Cell 3 received moisture addition incidents in July 1992, April 1993, and February 1994. Reported time zero corresponds to 23 October 1989. The data analyzed elapsed for about 10.5 yr for Cells 1 and 3 and about 7.5 yr for Cell 2. Collected data includes gas flow rate and methane percentage in the gas.

4.5.1.1 Brogborough Dry Cell 1

Gas collection data and fitted model curve are shown in Figure 4-5. The curve appears to rise starting at time zero with a relatively high rate. This can be explained by the fact that gas collection started in June 1992, whereas waste placement commenced in 1987.

The curve appears to be still rising at the end of the data set around day 3,900 and the L_0 estimate was found to be 144 m^3/Mg, whereas the maximum gas

Table 4-5. Best Model Parameters for Multiple Waste Placement Landfills

Landfill	k (yr^{-1})	L_0-V_{st0} (m^3/Mg)	$R^{2\,a}$	L_0[b] (m^3/Mg)	Notes
SSWMC	0.21 (0.057)	82 (5)	0.81	115	1.5 yr lag assumed
Landfill A	0.11 (0.011)	62 (2)	0.94	95	1.5 yr lag assumed
CSWMC	0.12 (0.026)	54 (5)	0.89	87	1.5 yr lag assumed

[a] R^2 is the square of the Pearson Correlation Coefficient.
[b] Based on an assumed V_{st0} of 33 m^3/Mg.

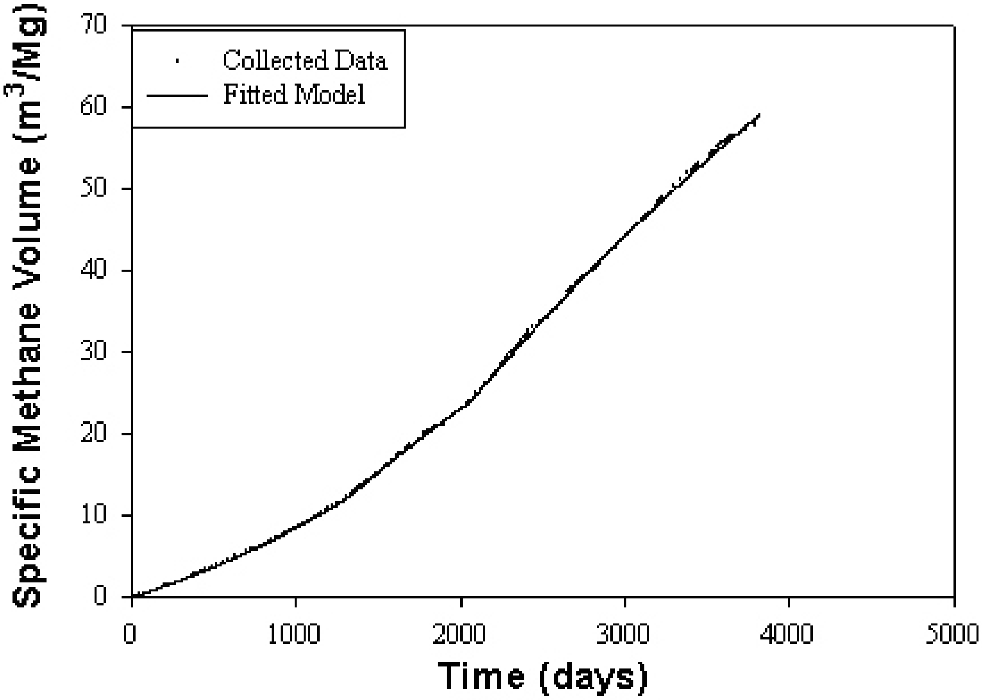

Figure 4-5. Brogborough Dry Cell 1 Data and Fitted Model Curve.

collected at that time was around 60 m^3/Mg. The k value of 0.072 yr^{-1} is expected for a dry cell and may be due to the apparent high L_0, which requires a long period of time to be reached. A bend is observed at the end tail of the data set; if more data were available, it could be verified if a maximum is being asymptotically approached. The values obtained are close to the existing estimates of parameters for dry cells of around 0.04 yr^{-1} for k and 140 m^3/Mg for L_0.

4.5.1.2 Brogborough Dry Cell 2

Brogborough Dry Cell 2 data and fitted model curve are shown in Figure 4-6. Similar to the first dry cell, the gas appears to rise immediately after time zero, as seen in Figure 4-6, for similar reasons as for cell 1. The L_0 estimate of 59 m^3/Mg is much larger than the gas collected until the end of gas monitoring (32 m^3/Mg) but less than the L_0 of 140 m^3/Mg for conventional landfills. The k of 0.22 yr^{-1} is larger than 0.04 yr^{-1} for conventional landfills since the ultimate L_0 predicted is low relative to the 144 m^3/Mg predicted for Dry Cell 1. Since L_0 was reached more quickly, k was higher. Though Cells 1 and 2 are both dry cells, it could not be explained why the gas production as well as parameter estimates were very different from one cell to the other. A possible reason can be that Cell 2 had a shorted period of gas collection (2800 days), at the end of which the curve starts to level off to a horizontal asymptote, whereas Cell 1 had longer period of has collection (3800 days) at the end of which the curve was still rising.

4.5.1.3 Brogborough Wet Cell

Brogborough Wet Cell data and fitted model curve are shown in Figure 4-7. The first break point (1331 days, or June 1993) comes a little after liquid injection took place in the landfill in April 1993. It is expected that few months of delay appear between liquid injection and high gas collection. On the other hand, liquid was injected in July 1992 and in February of 1994 (days 1,000 and 1,560) and no such behavior was observed. The second break point happened at day 2,058. A k value of 0.39 yr^{-1} is much higher than that observed for the two control dry

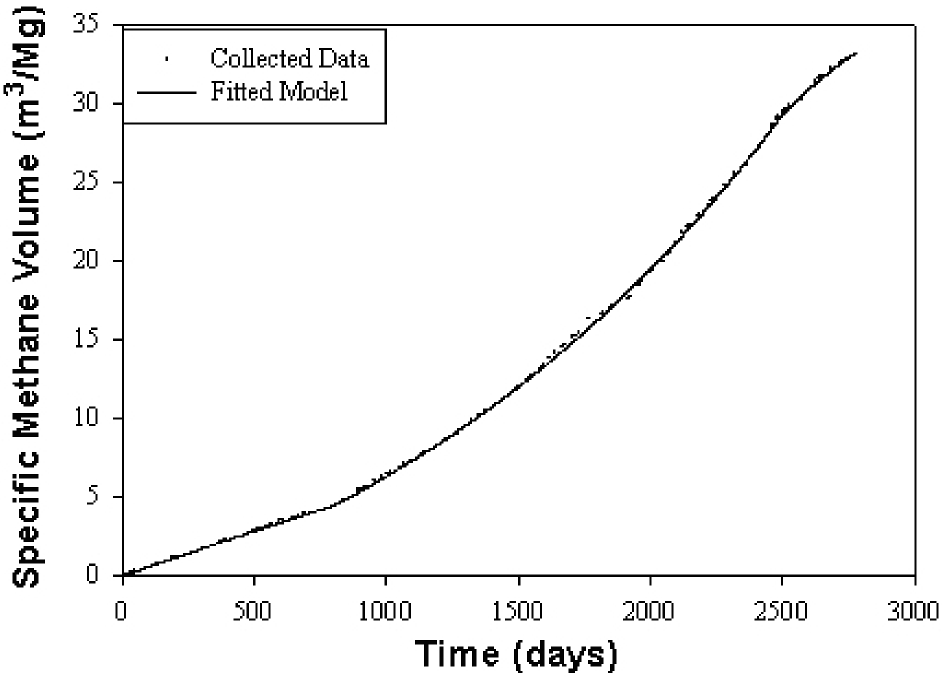

Figure 4-6. Brogborough Dry Cell 2 Collected Data and Fitted Model Curve.

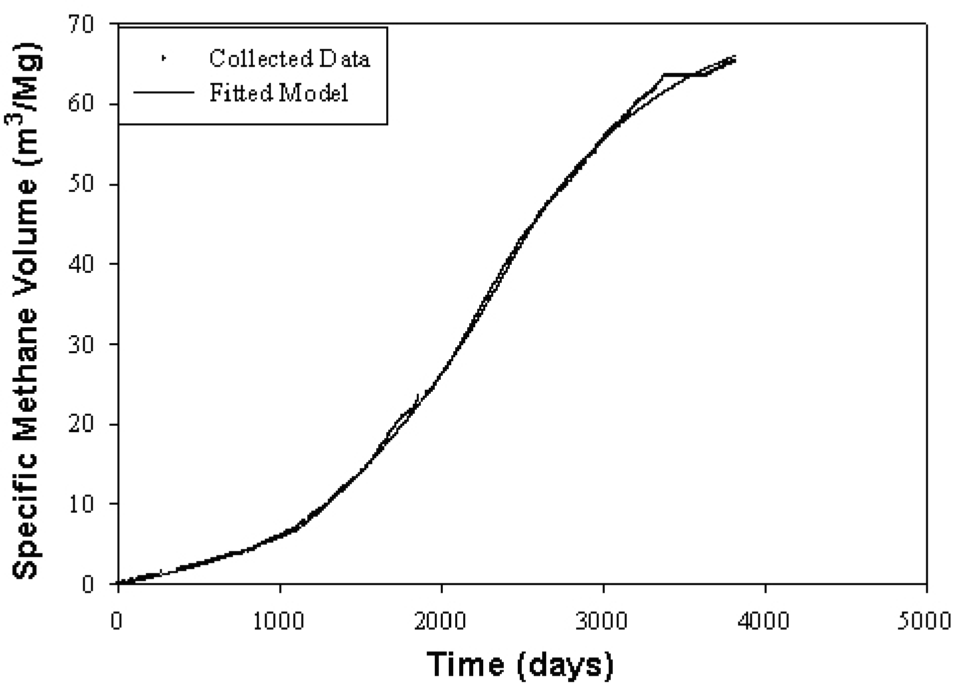

Figure 4-7. Brogborough Wet Cell Data and Fitted Model Curve.

cells. Conversely, the L_0 of 74 m^3/Mg is less than that found for the Dry Cell 1 (142 m^3/Mg). These results can be due to the fact that the gas production appears to be approaching an asymptote at the end of data collection of the wet cell. If more data were available from Dry Cell 1, a better model fit would be possible.

4.5.2 Yolo County Pilot Cells

Two test cells in Yolo County, California were filled with municipal solid waste from April through October 1995 with the final cover placed during November of 1995. The enhanced and control cells were filled with about 8,560 tons and 8,730 tons of waste, respectively. Leachate recirculation was initiated into the enhanced cell on day 133, with day 1 defined as the initiation of gas collection on June 12, 1996 (Mehta et al., 2002). The dry cell data were collected from June 12, 1996 untill June 13, 2000. The wet cell data start in June 12, 1996 and end in November 2003. The data include both methane percentage and gas flow rates.

4.5.2.1 Yolo County Pilot Dry Cell

As seen in Figure 4-8, an initial lag was experienced before the exponential rise started. This lag is not attributed to a change in gas recovery, since the final cap and gas collection system had already been in place at the time of gas collection and monitoring. The gas volume produced by the end of the lag phase was 19 m^3/Mg, which is approximately 66 percent of the calculated ultimate methane potential (28 m^3/Mg). It also appeared that gas generation had essentially stopped at year 2 since the curve approaches a maximum asymptotically at that point, presumably due to moisture limitations. This is further confirmed by recent data obtained for the dry pilot test cell beyond year 2000 and up to 2003 as explained below.

No explanation is available for the time of the break-points (days 208 and 431). The L_0 seems to approach a maximum of 28 m^3/Mg, which can be explained by moisture limitation for microorganisms. A high k of 2.5 yr^{-1} can be attributed to the relatively low L_0 that

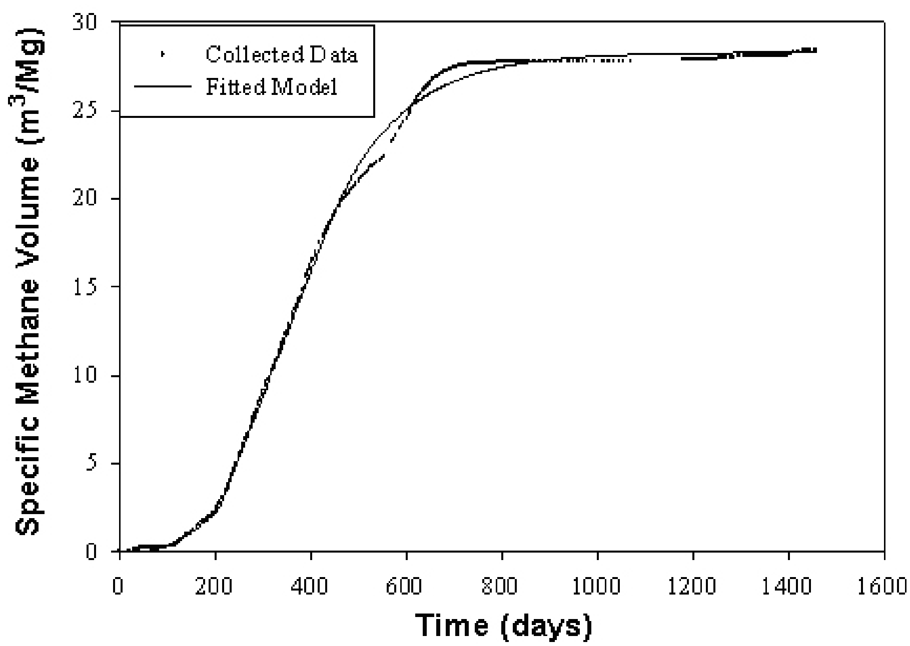

Figure 4-8. Yolo County Pilot Dry Cell Data and Fitted Model Curve.

was reached in a short time.

Some data for the dry cell became available later (through November 2003) and were also analyzed. However, only the previous presented data through year 2000 were considered in the data analysis. The more recent data showed a noticeable sudden increase in gas collection around day 2000, or December of 2001, as seen in Figure 4-9. Inquiry from Yolo County revealed that the leachate header located between the wet and dry cells was broken, and moisture was introduced into the dry cell, which triggered gas generation. Due to that leakage, leachate was detected in the control cell manhole that was otherwise dry for years (Private Yolo County correspondence data). Thus, the decline or cessation of gas collection was due to limitation in moisture, and once it was available, gas generation restarted. This incident indicates that the availability of moisture can be a limiting factor for gas generation. The full data set was analyzed and results obtained were 212 and 447 days for the break points, k of 1.78 yr^{-1} and L_0 of 30 m^3/Mg. However, only data prior to leachate leakage were used in the subsequent data analysis.

4.5.2.2 Yolo County Pilot Wet Cell

The Yolo County Pilot Wet Cell data and fitted model curve are shown in Figure 4-10. The first breakpoint (day 202) comes closely after beginning full-scale leachate injection in October 1996 (day 113). The second breakpoint, at 798 days, can be due to better acclimation of microorganism to waste. The calculated L_0 value of 88 m^3/Mg is more than double that calculated for the control cell (28 m^3/year), most likely due to the availability of moisture. A relatively high first-order rate constant was calculated for the dry cell (2.5 yr^{-1}), which is even higher than the rate constant for the enhanced cell (0.23 yr^{-1}). This apparent discrepancy can be explained by the fact that moisture is limiting in the dry cell; thus, the maximum methane production achieved was less than that of the enhanced cell. Less time was required to reach the maximum yield L_0 in the dry cell than the enhanced cell, which resulted in a higher k. This obser-

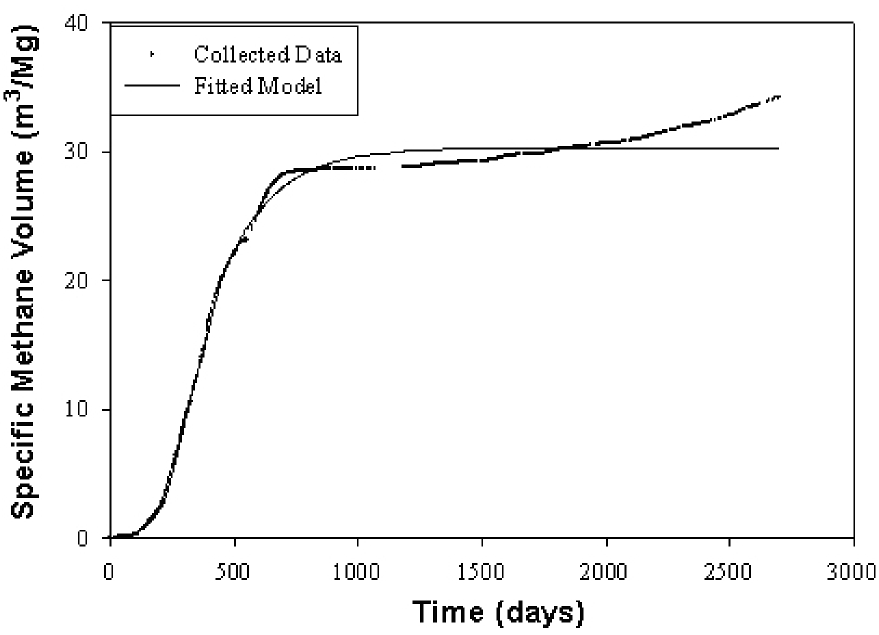

Figure 4-9. Yolo County Dry Pilot Cell Data and Fitted Model Curve (up to November 2003).

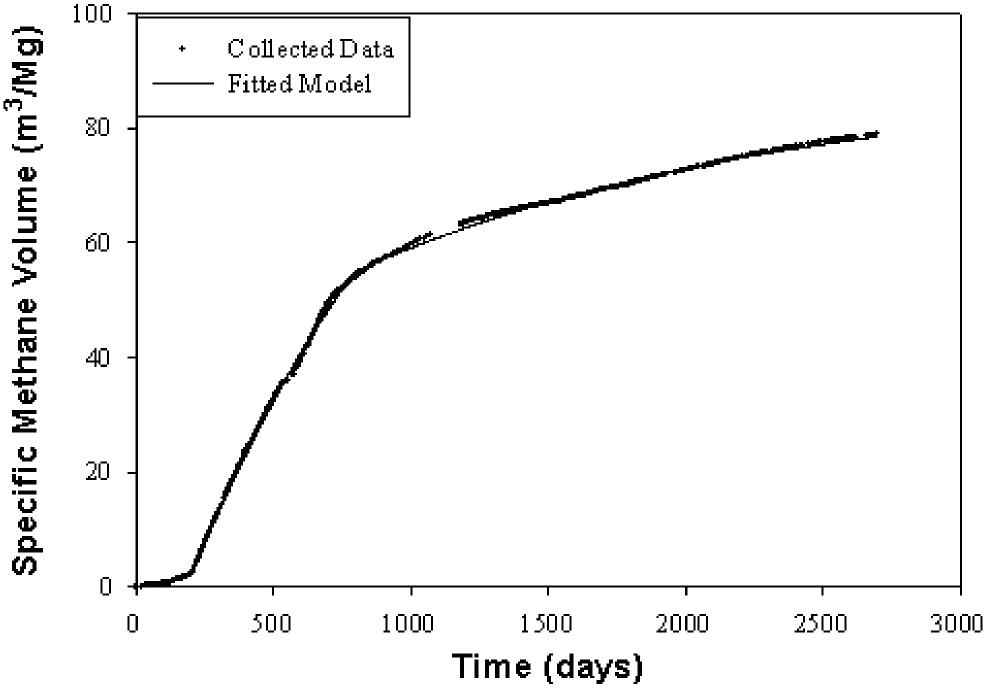

Figure 4-10. Yolo County Wet Pilot Cell Data and Fitted Model Curve.

vation is a mathematical anomaly and may not apply directly to other dry sites. However, the flow rate for the enhanced cell was higher at all times than that of the control cell, which was expected.

4.5.3 Yolo Full-Scale Cells

4.5.3.1 Yolo County NE

Yolo North East (NE) bioreactor cell is part of a full-scale anaerobic bioreactor project at Yolo County, CA. It contains about 69,000 Mg of waste. In March 2002 gas flow metering commenced and in the same month the leachate collection system was tested. Vacuum on the gas lines was increased for a waste sampling event in June 2002. Also in June 2002, full-scale leachate injection started. Data were obtained for gas flow rate and methane percentage for the period from December 2001 till December 2003. Gas collection data and fitted model curve are shown in Figure 4-11.

In June 2002 (around day 172), full-scale leachate injection started, after which the first breakpoint is observed at day 245. Leachate lines were also tested by the end of March 2002 (day 103) which could help produce the breakpoint. The *k* value obtained (0.20 yr^{-1}) is considerably higher than that of a dry landfill. The L_0 estimated was 83 m^3/Mg.

4.5.3.2 Yolo West Side Cell

As part of the Yolo County full-scale anaerobic bioreactor project, the Yolo West Side (WS) cell began accepting waste on March 8, 2001 and was completed on August 31, 2002 with a total of about 166,000 Mg of waste placed. The installation of the surface liner was completed in October 2002. In March 2003, gas collection laterals were hooked up to the main header line, and full-scale leachate addition started in June 2003. Gas flow rate and methane percentage data, starting in May 2002 and ending in December 2003, were analyzed. Collected gas data and fitted model curve are shown in Figure 4-12.

The first breakpoint (day 147) comes around the same time the surface liner installation started, and

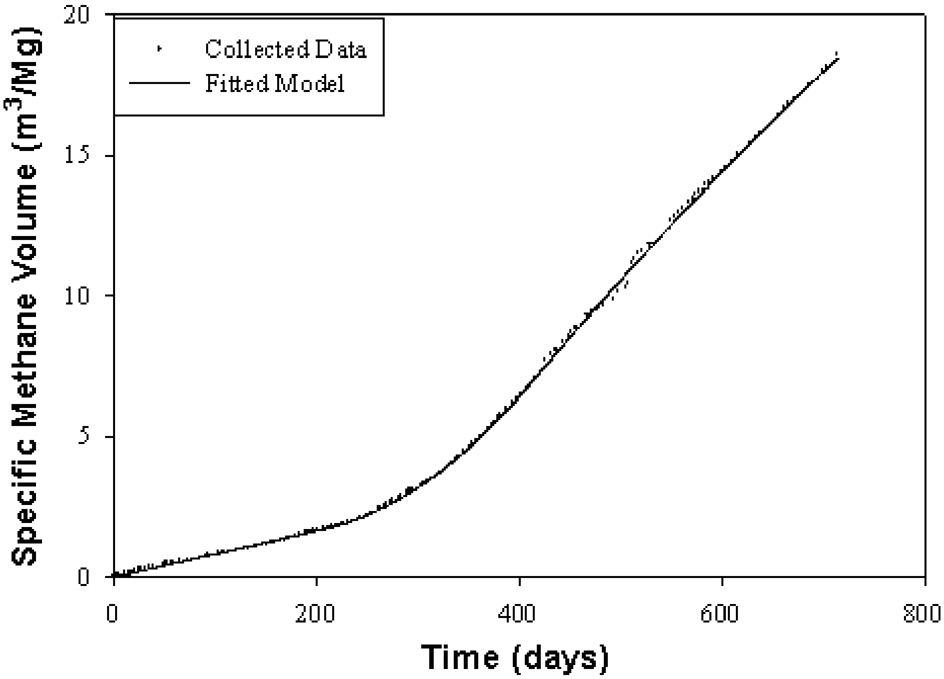

Figure 4-11. Yolo County NE Cell Data and Fitted Model Curve.

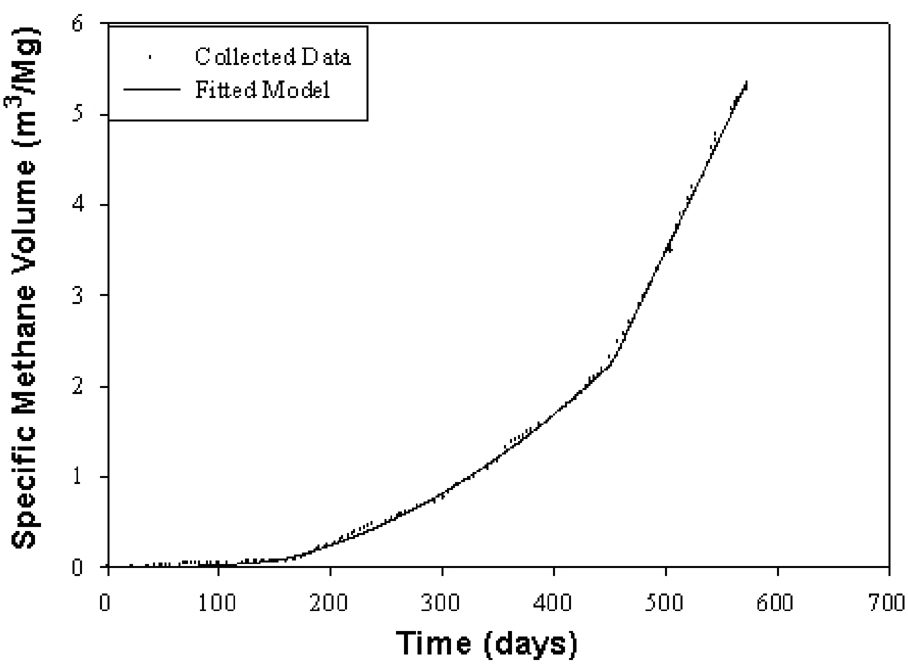

Figure 4-12. Yolo County WS Cell Data and Fitted Model Curve.

thus, more of the gas generated was being captured. Full-scale leachate injection started in September 2003 (around day 480), also close to the time of the second break point (487 days). The L_0 value of 9 m^3/Mg is not realistic and is probably due to short-term data available. The k value is very large (2.2 yr^{-1}) since L_0 was very small and was reached quickly. This site was included in estimating the regression parameters since more data are needed to obtain reasonable regression results.

4.5.4 Georgia Institute of Technology Simulated Landfill Columns

Approximately four years of data, consisting of collected gas volume and methane percentage, from two simulated landfill columns, control and wet, were reported in Pohland et al. (1993). Each lysimeter contained approximately 200 kg of waste.

Very long initial lag periods were observed and are due to acclimation of microorganisms in the lab study. The curve for the dry lysimeter was still on the rise at the conclusion of the study as seen in Figure 4-13. The first breakpoint of the dry lysimeter came at day 802 and the second at day 1257. The k was very high at 3.0 yr^{-1} and L_0 was 29 m^3/Mg.

The wet lysimeter started following the exponential trend of gas production at day 898 and had a k value of 1.7 yr^{-1} and an L_0 of 85 m^3/Mg. The bend at the end of the curve for the wet lysimeter as seen in Figure 4-14 indicates that the cumulative gas production was approaching the ultimate yield.

4.5.5 Delaware Solid Waste Authority Test Cells

The Delaware Solid Waste Authority (DSWA) constructed two test cells, a control cell and a bioreactor cell, containing approximately 7,500 tons and 8,300 tons, respectively. Gas flow rate and methane percentage data have been obtained from DSWA for the time period of August 1989 through December 1996. Cells were filled from August 1989 through July 1990. The cells were deconstructed in October 1996.

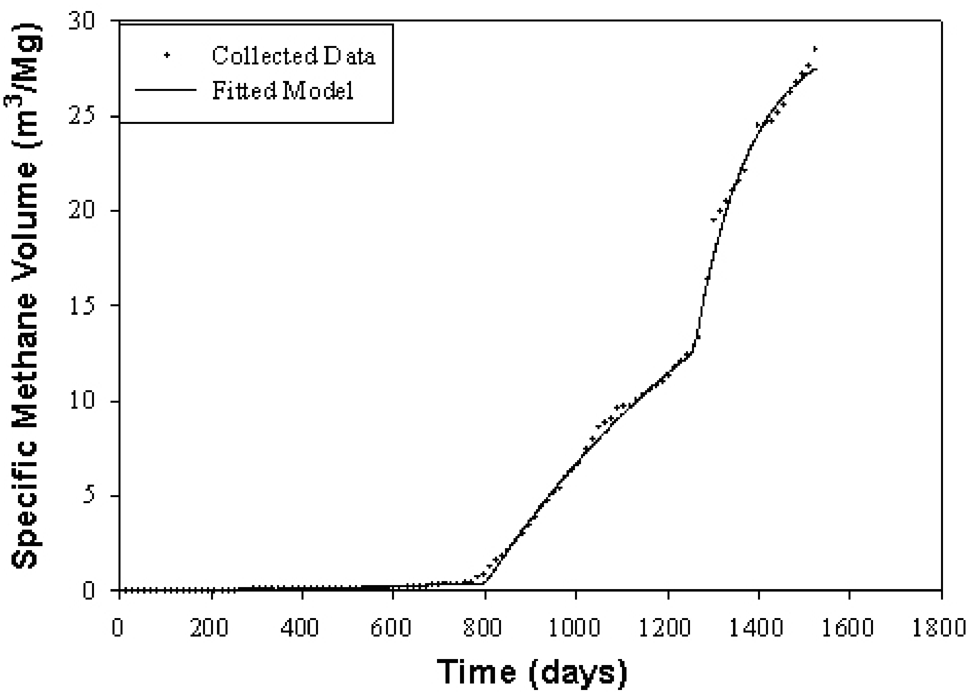

Figure 4-13. Georgia Tech Dry Lysimeter Data and Fitted Model Curve.

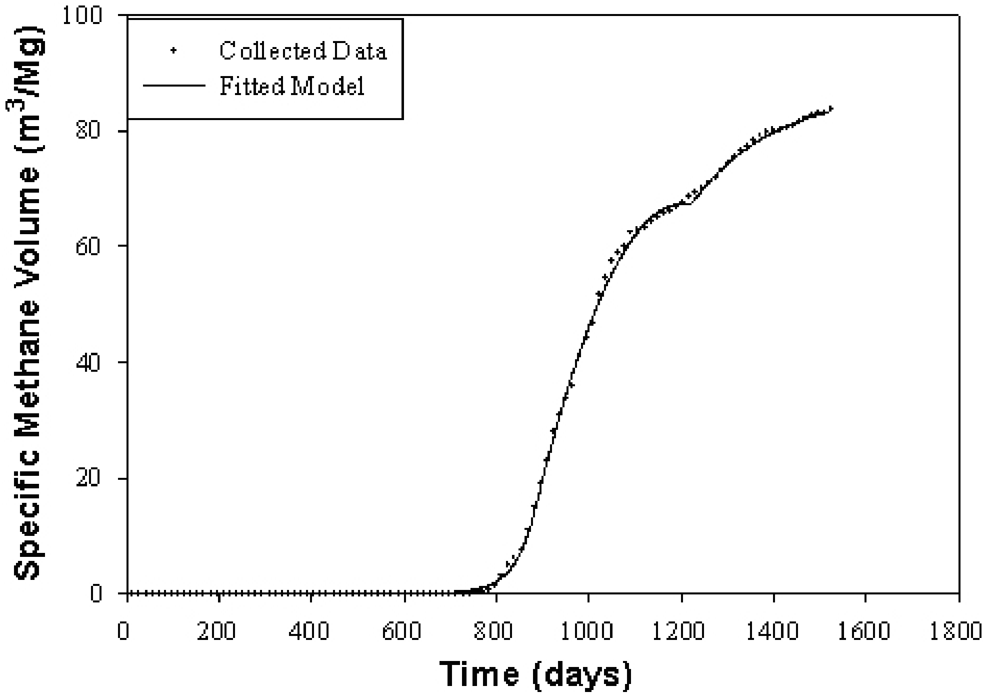

Figure 4-14. Georgia Tech Wet Lysimeter Data and Fitted Model Curve.

Extremely low methane gas was collected from these cells (0.022 m^3/Mg and 0.26 m^3/Mg for wet and dry cells, respectively). Figure 4-15 depicts the gas collection rates for both the wet and dry cell. According to DSWA personnel, upon excavation it was found that channeling of moisture had taken place, leaving most of the waste relatively dry and not decomposed. In addition, rapid rise in the gas volume right after the capping of both cells suggests that significant amount of gas may have been lost during the year of cells filling prior to capping. Even if the gas generated during the year of waste placement had been captured, the ultimate gas collection was still very low. Since gas collected was unreasonably low, the DSWA Test Cells data were not used in the parameter determinations.

4.6 Discussion of the Multiple Placement Cells with Continuous Flow Data

4.6.1 Southern Solid Waste Management Center

Data from the Southern Solid Waste Management Center (SSWMC) in Delaware were obtained for experimental cells 1 and 2, which comprise one contiguous landfill area. Data collected represent gas collection for the entire area. Leachate recirculation took place in both Cells 1 and 2; however, Cell 2 received approximately 60,000 gallons of recirculated leachate while Cell 1 received 4,000,000 gallons. Gas flow and composition data were obtained from DSWA for the period of January 1995 through April 2002. Cells 1 and 2 received waste from 1985 until 1997. Gas collection from Cell 1 and Cell 2 began in June 1994 and July 1997, respectively.

As seen in Figure 4-16, gas flow rates appear to increase until 1998, at the time of startup of the Cell 2 gas collection system. Therefore, only the data points after 1998 have been used for regression analysis. The model parameters found from regression analysis of data after 1998 were used to generate the gas collection curve (as flow rates) for the period from 1995 to 2002 by putting the parameters into a spreadsheet set up to calculate the gas generation based on the yearly waste placement. The difference

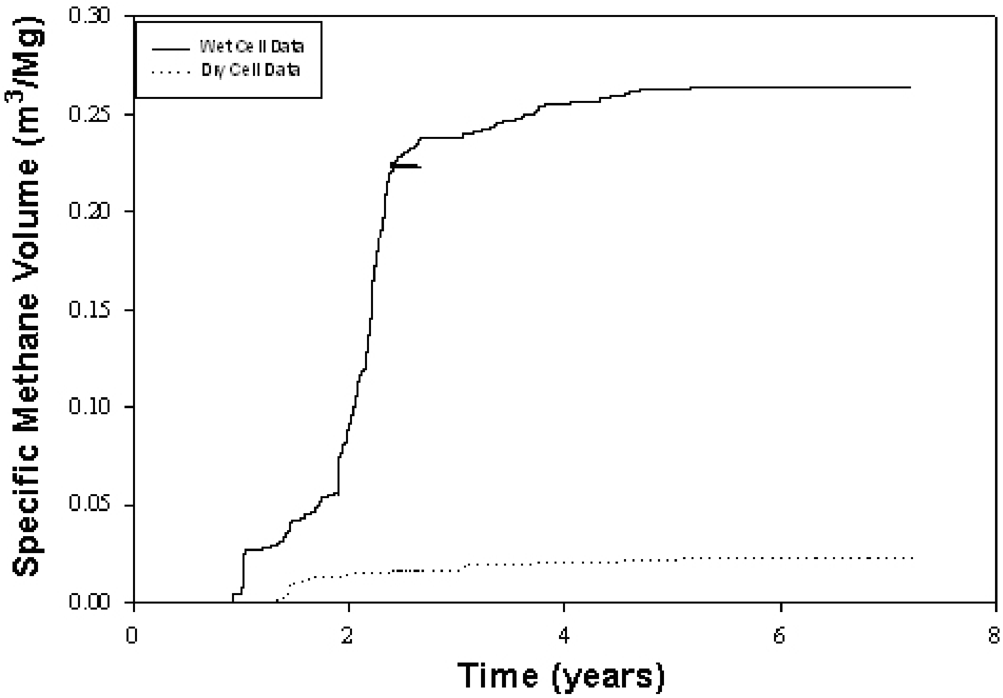

Figure 4-15. DSWA Test Cells Data and Fitted Curves, Time Zero=1989.

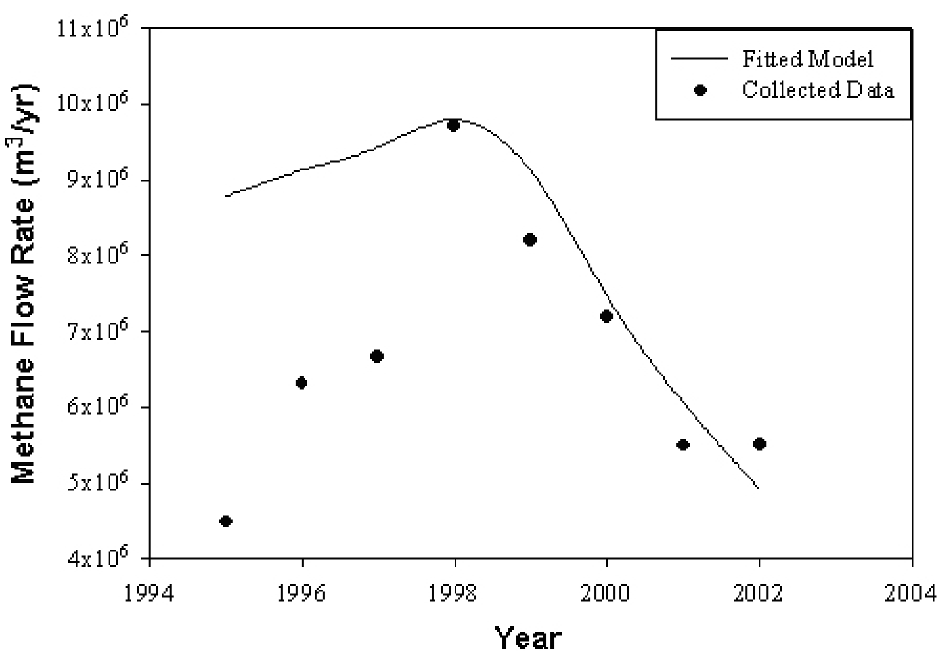

Figure 4-16. SSWMC Collected Data and Fitted Model Curve.

between the generated curve and the collected data points prior to 1998 can provide information about the percentage of recovery of gas while Cell 2 was in operation prior to closure and capping. Since the lag can not be modeled with the limited data available and without having the initial gas production data immediately after waste placement, a lag of 1.5 years as calculated in Section 4.3.2 was used. Parameters estimated were 0.21 yr^{-1} for k and 82 m^3/Mg for ($L_0 - V_{st0}$). If a V_{st0} of 33 m^3/Mg is assumed as found in Section 4.3.3, L_0 would be 115 m^3/Mg. If no lag was assumed, then k and ($L_0 - V_{st0}$) values would be 0.158 yr^{-1} and 139 m^3/Mg, respectively.

4.6.2 Landfill A

In Landfill A, wetting occurred due to groundwater inflow into the base of the waste from an unconfined aquifer. The cell received 1,600,000 Mg of waste from 1976 until 1992. Quantitative and qualitative waste and gas data were obtained for the time period of November 1993 until August 2000. The results found from the analysis of Landfill A were 0.11 yr^{-1} for k and 62 m^3/Mg for ($L_0 - V_{st0}$) and were all collected after the closure of the landfill cell. The fitted model curve and collected data can be seen in Figure 4-17.

4.6.3 Central Solid Waste Management Center

The Central Solid Waste Management Center bioreactor is owned and operated by the DSWA. Approximately 79,000 Mg of waste was placed in this landfill cell from 1981 until 1988 after which a sandy soil cover was placed. Gas collection from areas A, B, C, and D started in 1996. Leachate was recirculated at the site from 1985 to 1995. Gas flow data were available from 1997 till 2003, with data for 2000, 2001, and a part of 2002 missing. Gas quality was also available for the period mentioned. Parameter estimate were 0.12 yr^{-1} for k and 54 m^3/Mg for ($L_0 - V_{st0}$). The fitted model curve and collected data can be seen in Figure 4-18.

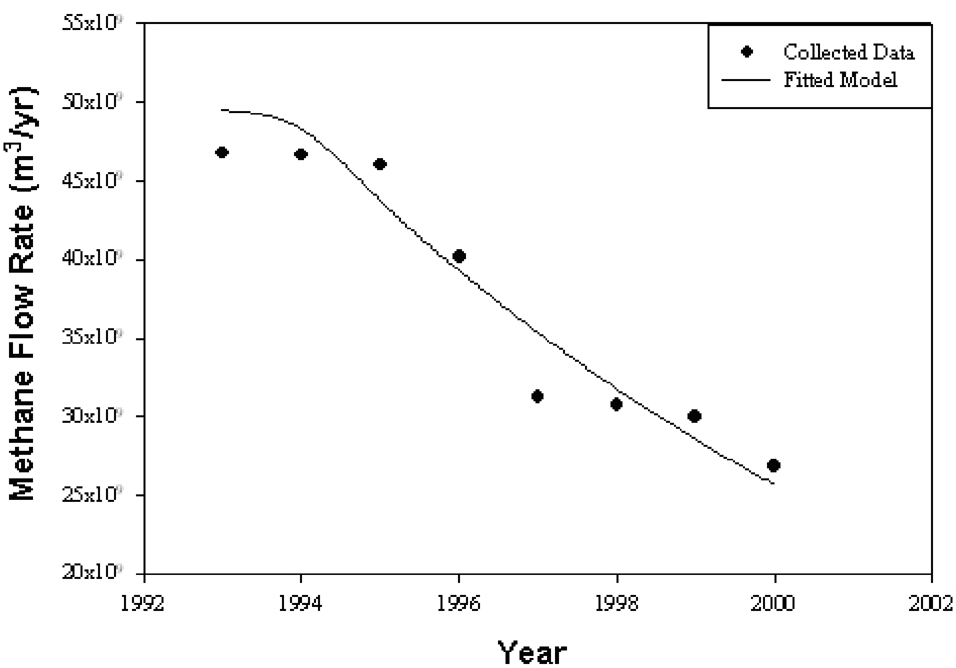

Figure 4-17. Landfill A Collected Data and Fitted Model Curve.

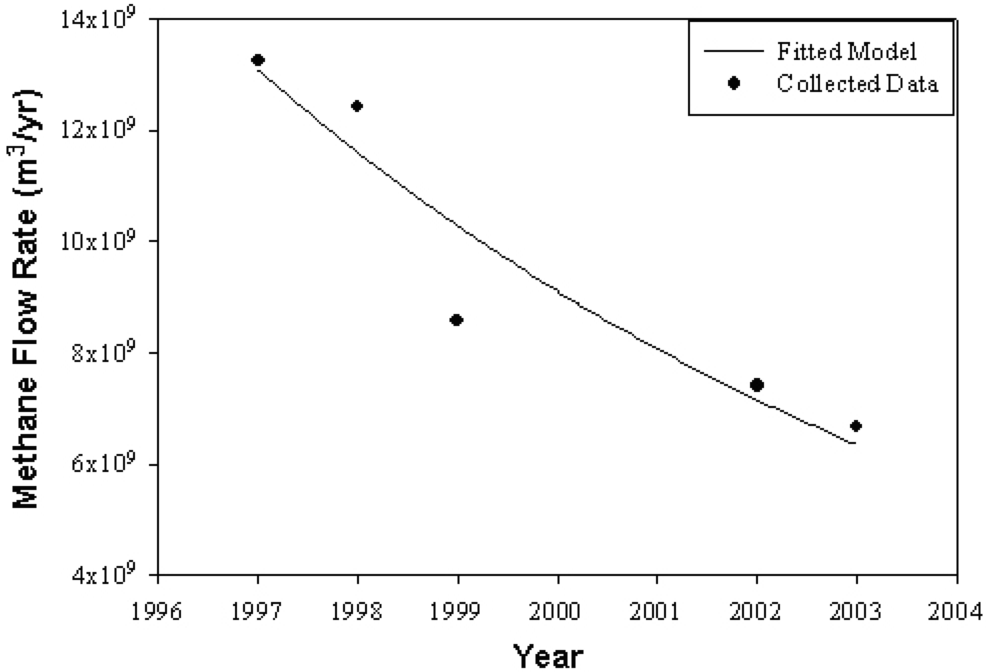

Figure 4-18. CSWMC Collected Data and Fitted Model Curve.

4.7 Single Data Points Results and Discussion

Data from 21 full-scale landfills were analyzed as described in Section 3.5.3 and are presented in Figure 4-19. Several of these older landfills actually did not begin recirculating leachate until just prior to reporting gas collection data; consequently, once the waste becomes wet, gas generation would significantly be enhanced. It would appear that due to delayed leachate recirculation, non-optimal moisture conditions, poor gas capture, and other site-specific reasons, early collection flow rates are often significantly lower than would be expected. The landfills with weighted age less than 2 years in Figure 4 19 appear to still be experiencing a lag in gas collection.

The "Best Fit Mixed-Effects Model Curve" in Figure 4-19 was generated using the set of parameters determined from the mixed-effects model having a k of 0.28 yr^{-1} and an L_0 of 76 m^3/Mg. The lower confidence band had a k of 0.28 yr^{-1} and an L_0 of 54 m^3/Mg. The upper confidence band had a k of 0.28 yr^{-1} and an L_0 of 96 m^3/Mg. The lag was accounted for by shifting the points on the x-axis assuming a lag of 1.5 yr occurred. Since lag is assumed, the model that accounts for a lag was used, with V_{st0} values of 33, 0, and 77 m^3/Mg for the mean, lower and upper curves, respectively. Figure 4-20 is a more "conservative" one, where it is assumed that lag did not occur, and thus V_{st0} was zero. It can be seen that it estimates higher gas generation, which would be an expected scenario with early moisture addition, early capping, and early collection of gas. Some of the full scale landfills had very late liquid addition, late capping, or were otherwise dry for a long time before operating as wet landfills. Consequently, the lower gas generation is observed, in contrast to landfills that would be optimized as wet landfills from their start up.

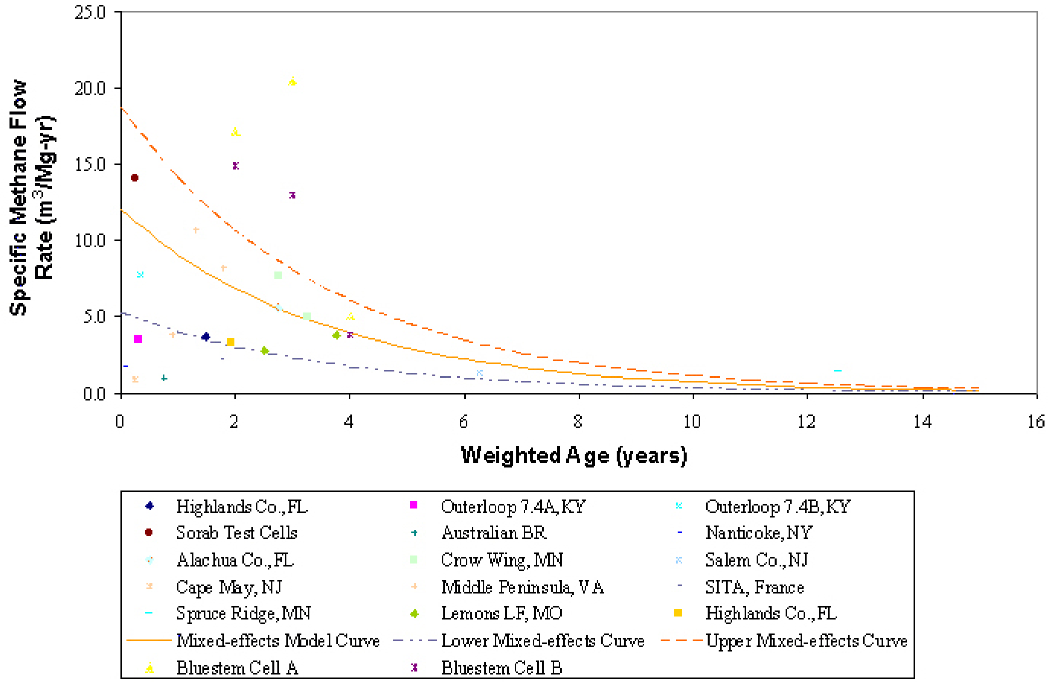

Figure 4-19. Single Points and Mixed-Effects Model Curve with 95 Percent Confidence Band.

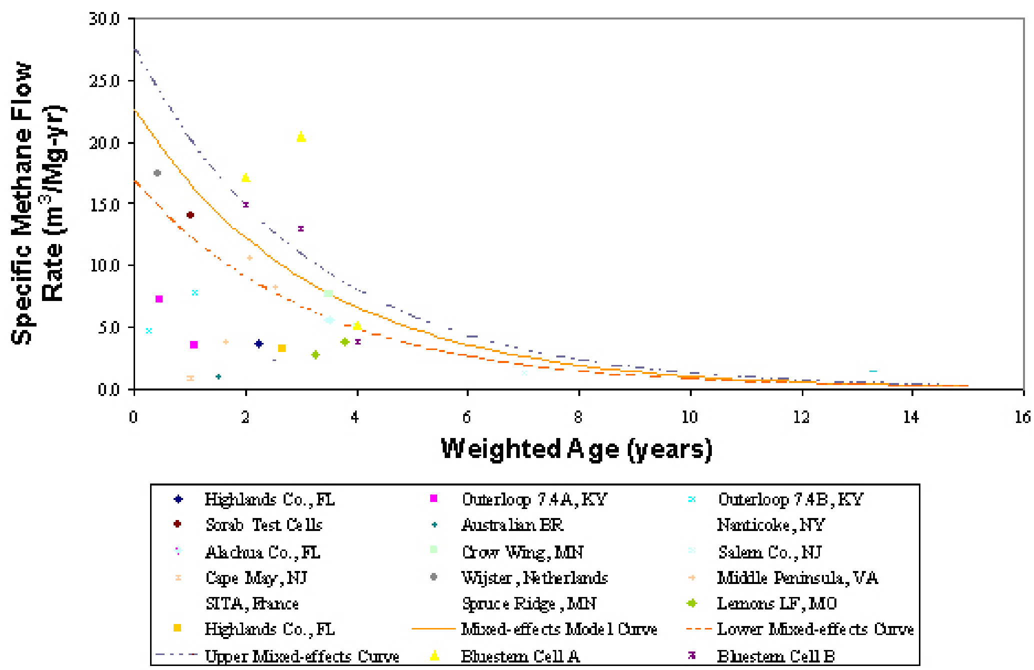

Figure 4-20. Single Points and Mixed-Effects Model Curve with 95 Percent Confidence Band with No Lag Assumed.

Chapter 5
Conclusion And Recommendations

5.1 Significance of this Study

This report presents the most comprehensive study to date to estimate the gas emission parameters for wet landfills. The available gas emission parameters that are suggested in literature are either based on a small-scale lysimeters or otherwise solely based on theoretical modeling. Even in cases where real data have been modeled, very few data points for single sites have been used. Moreover, the techniques used to analyze the data using statistical computer software to find parameters for both wet and dry cells are more robust than the trial and error techniques often used in previous modeling studies.

5.2 Conclusions and Recommendations

The first-order model seems to fit the data analyzed quite well provided it is preceded by a lag phase. The lag phase is usually composed of two time periods that take different forms. A lag phase is observed for sites with continuous data and for some full-scale single data point sites as well. An average lag of about 1.5 yr was estimated to occur prior to gas generation for the wet landfills analyzed. A longer lag may be experienced in dry cells; however, because of the lengthy period of gas generation experienced in dry landfills, consideration of a lag period may not be as important. It is suggested to use a volume-based form of the LandGEM model, which takes the form in Equation 5-1 when incorporating a lag phase.

$$V = \sum_{i=1}^{n} M_i \left\{ V_{st0} + \left(L_0 - V_{st0}\right)\left[1 - e^{-k\left(t_i - t_0\right)}\right]\right\} \qquad 5\text{-}1$$

Taking the derivative of Equation 5-1 gives the flow rate model, Equation 5-2.

$$Q_{CH4} = \sum_{i=1}^{n} kM_i \left(L_0 - V_{st0}\right) e^{-k\left(t_i - t_0\right)} \qquad 5\text{-}2$$

Where:
- t_0 = lag time; and
- V_{st0} = specific methane volume produced during the lag phase.

If it is assumed that 50 percent of gas is methane, the gas flow rate can be calculated using Equation 5-3.

$$Q = 2\sum_{i=1}^{n} kM_i \left(L_0 - V_{st0}\right) e^{-k\left(t_i - t_0\right)} \qquad 5\text{-}3$$

Where:
- Q = gas flow rate in cubic meters per year.

It must be emphasized that the data presented and analyzed in this report are collected gas data, not generated data, and as gas collection efficiency is improved different conclusions may be reached.

When using LandGEM to determine gas flow rates using a k greater than 0.1 yr^{-1}, it is recommended that a time step of 0.1 yr or smaller be used. The model should be amended to use the cumulative volume equation. Differences are not huge, but more accuracy will be obtained. When the 0.1 year time step is incorporated, the model can be described by Equation 5-4.

$$Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} \frac{kM_i}{10}\left(L_0 - V_{st0}\right)e^{-k\left(t_{ij}-t_0\right)} \qquad 5\text{-}4$$

Where:

- i = 1 yr time increment for waste placement;
- n = number of years of waste acceptance;
- j = 0.1 yr time increment for methane production calculation;
- M_i = mass of waste accepted in the i^{th} year in megagrams); and
- t_{ij} = age of the j^{th} section of waste mass M_i accepted in the i^{th} year (decimal years, e.g., 3.2 years).

Wet cells were observed to produce more gas at a faster rate than conventional landfills; particularly after closure and more effective wetting was occurring. Landfill closure increased the gas collection efficiency, as seen in the case of SSWMC. Even if a gas collection system is operational, a lack of cover will reduce the collection efficiency. Gas generation at dry cells appeared to be inhibited, probably due to moisture limitation. Thus, the ultimate methane potential may not be achievable in dry cells.

Model parameters are highly dependent on moisture conditions and capture efficiency. Unfortunately both of these values are site specific and difficult to quantify. More data from full-scale landfills are needed with complete data sets that provide descriptions of gas collection systems, gas quality and quantity, waste placement rates, and moisture conditions. Moreover, newer data from the analyzed sites should be gathered and incorporated in the study. In the future, long-term gas data should be analyzed since currently very few sites have such data available.

For similar L_0, a higher k (typical of a wet cell) predicts a higher gas generation rate than a lower k (typical of a dry cell). However for different L_0, a higher k may only suggest a shorter time at which the maximum yield is achieved and does not necessarily predict higher collection rates. Consequently, it is important to evaluate both k and L_0 when modeling gas production.

Table 5-1 summarizes the k and L_0 parameter estimates from this study. For the three full-scale multiple placement sites (SSWMC, Landfill A, and CSWMC), the amount of gas produced during the lag phase, V_{st0}, was assumed to be the same as the values found from the mixed-effects model for the single placement sites. Although the gas produced in the lag phase (V_{st0}) was often found to be a significant percentage of total gas generation potential (L_0), it is expected that, as wet landfill design is optimized and liquid addition commences shortly after waste placement, gas collection will start earlier and V_{st0} will be minimized. Then, the L_0 estimates would be suitable for use in a model without a lag, thus neglecting the V_{st0}. Therefore, a conservative set of LandGEM parameters for wet landfills would be a k of 0.3 yr^{-1} and an L_0 of 100 m^3/Mg.

Table 5-1. Summary Table for Parameter Estimation[a]

Method	k (yr^{-1})	L_0 (m^3/Mg)
Single Placement Sites		
Brogborough Wet	0.39	73
Yolo Full-Scale NE	0.20	83
Yolo Pilot Wet	0.23	88
Multiple Placement Sites		
SSWMC	0.21	115
Landfill A	0.11	95
CSWMC	0.12	87
Mixed-Effects Model		
Mean	0.28	76
Upper 95%	0.28	96
Lower 95%	0.28	54

[a] V_{st0} = 33 m^3/Mg and t_0 = 1.5 yr in Equation 5-2.

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Appendix

Table A-1. Parameters Summary for Fitted Models

Landfill	Lag Type	df	d_0 (days)	t_0 Days)	k (yr^{-1})	L_0 (m^3/Mg)	RSS	*AIC*	*BIC*
	No lag	2			4.89×10^{-5}	72,644.0	57,713.3	2006.0	2007.4
	Exp	5		2331	0.080	134.2	59.0	454.0	457.6
	Exp-Exp	8	102	2254	0.073	137.0	546.7	963.7	969.5
	Exp-Lin	7	1272	2096	0.073	142.0	39.9	369.4	374.4
	Exp-Quad	**8**	**1331**	**2056**	**0.072**	**144.0**	**39.0**	**366.3**	**372.0**
Brogborough Dry 1	Lin	4	[a]						
	Lin-Exp	7	485	2571	0.146	95.1	67.6	488.8	493.8
N=521	Lin-Lin	6	1048	2070	0.072	143.6	51.4	424.8	429.1
	Lin-Quad	7	799	2164	0.076	138.3	47.2	407.5	412.5
	Quad	5		2170	0.077	138.1	48.7	410.5	414.1
	Quad-Exp	8	44	2394	0.084	131.2	85.7	544.5	550.3
	Quad-Lin	7	1258	2096	0.073	142.0	40.0	369.9	375.0
	Quad-Quad	8	1307	2060	0.072	144.0	39.1	367.0	372.7
	No lag	2			8.36×10^{-5}	31,272.2	12,138.0	1230.2	1231.4
	Exp	5		2387	0.799	37.6	22.3	223.7	226.5
	Exp-Exp	**8**	**798**	**2501**	**0.544**	**41.0**	**10.8**	**113.3**	**117.8**
	Exp-Lin	7	778	2132	0.398	45.2	185.3	568.2	572.2
	Exp-Quad	8							
Brogborough Dry 2	Lin	4							
	Lin-Exp	7	24	2347	0.595	40.1	23.0	232.9	236.9
N=370	Lin-Lin	6	1031	1998	0.193	62.6	21.8	222.4	225.8
	Lin-Quad	7	825	2072	0.215	59.1	12.2	130.6	134.5
	Quad	5	825	2061	0.216	59.0	22.6	226.0	228.9
	Quad-Exp	8	18	2265	0.360	46.5	22.1	228.5	233.0
	Quad-Lin	7	1267	2040	0.215	59.0	14.2	155.0	159.0
	Quad-Quad	8	374	2392	0.942	36.9	12.4	135.6	140.1

Continued

Table A-1. Parameters Summary for Fitted Models (continued)

Landfill	Lag Type	df	d_0 (days)	t_0 Days)	k (yr^{-1})	L_0 (m^3/Mg)	RSS	*AIC*	*BIC*
Brogborough Wet N=521	No lag	2			6.85×10^{-5}	72,540.4	48,764.3	1967.9	1969.3
	Exp	5		1498	0.160	100.9	1073.9	1110.5	1114.1
	Exp-Exp	**8**	**1106**	**2404**	**0.394**	**73.5**	**139.5**	**654.7**	**660.4**
	Exp-Lin	7	2044	2328	0.365	75.0	272.6	804.3	809.3
	Exp-Quad	8	1031	2427	0.398	73.3	140.0	655.5	661.2
	Lin	4		1498	0.160	100.9	1073.9	1108.5	1111.4
	Lin-Exp	7	1139	2088	0.342	75.9	179.2	709.4	714.4
	Lin-Lin	6	1136	2087	0.342	75.9	179.3	707.5	711.8
	Lin-Quad	7	1089	1986	0.328	76.7	187.4	719.5	724.5
	Quad	5		2132	0.351	75.4	228.3	760.2	763.7
	Quad-Exp	8	1999	2430	0.383	73.8	211.6	749.0	754.7
	Quad-Lin	7	1281	2110	0.346	75.6	157.2	679.7	684.7
	Quad-Quad	8	1023	2427	0.398	73.3	140.6	656.5	662.2
Yolo County North East Wet Cell N=163	No lag	2			3.14×10^{-4}	13,695.7	2521.8	491.0	491.4
	Exp	5		432	0.293	60.5	3.2	23.8	24.9
	Exp-Exp	8	378	658	2.624	21.7	178.6	315.6	317.3
	Exp-Lin	7	448	487	0.631	36.1	2.8	19.6	21.1
	Exp-Quad	8	459	484	0.639	35.8	2.8	22.4	24.1
	Lin	4		302	0.047	310.0	5.1	55.8	56.6
	Lin-Exp	7	222	389	0.270	64.1	1.5	-25.0	-23.5
	Lin-Lin	6	245	347	0.198	83.2	1.7	-19.8	-18.5
	Lin-Quad	7	208.8	426	0.279	62.8165	1.6	-22.1	-20.6
	Quad	5		327	0.142	110.7	2.8	14.8	15.9
	Quad-Exp	8	319	512	0.551	38.5	2.7	18.3	20.0
	Quad-Lin	7	302	383	0.268	64.8	2.1	0.4	1.9
	Quad-Quad	**8**	**206**	**394**	**0.275**	**63.4**	**1.4**	**-25.4**	**-23.7**
Yolo County West Side Cell N=118	No Lag	2			3.53×10^{-4}	1549.3	267.8	258.2	258.3
	Exp	5		505	3.723	7.0	0.6	-51.6	-51.2
	Exp-Exp	8	144	496	4.015	6.8	0.3	-87.0	-86.4
	Exp-Lin	7	242	488	3.687	7.1	2.2	21.3	21.8
	Exp-Quad	8	160	452	0.073	132.7	0.2	-112.2	-111.7
	Lin	4							
	Lin-Exp	**7**	**147**	**487**	**2.230**	**8.7**	**0.2**	**-96.6**	**-96.1**
	Lin-Lin	6							
	Lin-Quad	7							
	Quad	5							
	Quad-Exp	8	143	496	4.015	6.9	0.2	-92.5	-91.9
	Quad-Lin	7	486	489	2.230	8.7	0.6	-42.2	-41.7
	Quad-Quad	8							

continued

Table A-1. Parameters Summary for Fitted Models (continued)

Landfill	Lag Type	df	d_0 (days)	t_0 Days)	k (yr^{-1})	L_0 (m^3/Mg)	RSS	*AIC*	*BIC*
	No lag	2			5.88×10^{-1}	34.4	7491.3	1730.9	1732.5
	Exp	5		277	2.008	28.5	441.0	1003.8	1007.6
	Exp-Exp	8	145	353	2.274	28.4	116.8	665.9	672.1
	Exp-Lin	7	192	543	5.658	28.0	206.5	811.4	816.8
	Exp-Quad	8	99	330	2.044	28.4	204.9	811.3	817.5
Yolo County Pilot Dry Cell	Lin	4		248	1.869	28.7	351.0	942.7	945.8
	Lin-Exp	7	171	385	2.362	28.4	146.0	721.6	727.0
N=521	Lin-Lin	6	191	436	2.540	28.3	117.4	663.2	667.8
	Lin-Quad	7	99	330	2.044	28.4	204.9	809.3	814.8
	Quad	5		365	2.296	28.3	184.6	778.3	782.2
	Quad-Exp	8	203	490	3.197	28.2	126.5	686.5	692.7
	Quad-Lin	**7**	**208**	**431**	**2.504**	**28.3**	**111.3**	**651.4**	**656.8**
	Quad-Quad	8	61	393	2.697	28.2	203.9	810.1	816.3
	No lag	2			3.69×10^{-1}	85.7	24,276.5	2035.2	2036.8
	Exp	5		245	0.712	75.1	2352.3	1437.1	1441.0
	Exp-Exp	8	204	296	0.715	75.0	2340.0	1441.7	1447.9
	Exp-Lin	7	177	735	0.273	85.9	439.9	1007.1	1012.5
	Exp-Quad	**8**	**202**	**798**	**0.234**	**88.4**	**212.0**	**820.2**	**826.4**
Yolo County Pilot Wet Cell	Lin	4		210	0.708	75.1	2366.7	1436.7	1439.8
	Lin-Exp	7	196	794	0.235	88.3	215.0	821.8	827.2
N=596	Lin-Lin	6	170	735	0.272	85.9	442.2	1006.5	1011.1
	Lin-Quad	7	195	798	0.234	88.4	217.3	824.6	830.0
	Quad	5		219	0.708	75.1	2354.6	1437.3	1441.2
	Quad-Exp	8	202	497	0.675	75.0	3164.7	1519.9	1526.1
	Quad-Lin	7	175	735	0.272	85.9	440.1	1007.2	1012.7
	Quad-Quad	**8**	**200**	**798**	**0.234**	**88.4**	**212.0**	**820.2**	**826.4**
	No Lag	2			5.31×10^{-5}	64,594.5	3431.8	363.3	363.4
	Exp	5		1339	1.321	35.6	90.7	197.3	197.5
	Exp-Exp	8	995	1257	2.964	29.4	13.4	112.8	113.1
	Exp-Lin	7	971	1259	2.964	29.4	13.0	109.2	109.5
	Exp-Quad	8	414	1271	2.887	29.5	34.2	157.1	157.4
Georgia Tech Dry Lysimeter	Lin	4							
	Lin-Exp	7							
N=109	Lin-Lin	6	766	1261	2.887	29.5	14.2	111.6	111.9
	Lin-Quad	7	414	1271	2.887	29.5	34.2	155.1	155.4
	Quad	5		1257	2.964	29.403	85.7	194.6	194.8
	Quad-Exp	**8**	**802**	**1257**	**2.964**	**29.403**	**11.4**	**105.1**	**105.4**
	Quad-Lin	7	772	1262	2.887	29.537	14.1	113.1	113.3
	Quad-Quad	8	772	1262	2.887	29.5	14.1	115.1	115.4

continued

Table A-1. Parameters Summary for Fitted Models (concluded)

Landfill	Lag Type	df	d_0 (days)	t_0 Days)	k (yr^{-1})	L_0 (m^3/Mg)	RSS	*AIC*	*BIC*
Georgia Tech Wet Lysimeter N=109	No Lag	2			1.19×10^{-4}	111,078.0	44,437.5	484.5	484.6
	Exp	**5**		**898**	**1.712**	**85.4**	**144.6**	**219.4**	**219.6**
	Exp-Exp	8	800	868	1.712	85.0	724.8	301.7	302.0
	Exp-Lin	7	775	862	1.726	85.3	141.3	222.3	222.5
	Exp-Quad	8	807.3	861.7	1.726	85.312	139.9	223.8	224.1
	Lin	4		835	1.632	86.3	194.4	231.4	231.5
	Lin-Exp	7	769	907	1.712	85.4	140.0	221.9	222.1
	Lin-Lin	6	786	863	1.726	85.3	140.3	220.0	220.2
	Lin-Quad	7	769	870	1.737	85.2	140.5	222.0	222.3
	Quad	5		837	1.632	86.3	188.0	231.8	232.0
	Quad-Exp	8	777	870	1.737	85.2	140.4	224.0	224.3
	Quad-Lin	7	786	863	1.726	85.3	140.3	220.0	222.2
	Quad-Quad	8	753	870	1.737	85.2	140.5	224.0	224.3

[a] Calculations did not converge for cells without data.

Table A-2. Best Model for Each Landfill

Landfill	Lag Type	df	d_0 (days)	t_0 Days)	k (yr^{-1})	L_0 (m^3/Mg)	RSS	*AIC*	*BIC*
Brogborough Dry 1	Exp-Quad	8	1331	2058	0.072	144	39.0	366.3	372.0
Brogborough Dry 2	Lin-Quad	**7**	825	2072	0.22	59	12.2	130.6	134.5
Brogborough Wet	Exp-Exp	8	1106	2404	0.39	74	139.5	654.7	660.4
Yolo Full-Scale NE	Lin-Lin	6	245	347	0.20	83	1.7	-19.8	-18.5
Yolo Full-Scale WS	Lin-Exp	7	147	487	2.2	9	0.2	-96.6	-96.1
Yolo Pilot Dry	Quad-Lin	7	208	431	2.5	28	111.3	651.4	656.8
Yolo Pilot Wet	Exp-Quad	8	202	798	0.23	88	212.0	820.2	826.4
Georgia Tech Dry	Quad-Exp	8	802	1257	3.0	29	11.4	105.1	105.4
Georgia Tech Wet	Exp	5		898	1.7	85	144.6	219.4	219.6

Table A-3. Mixed-Effects Model Results

	Fixed	Random	*AIC*	*BIC*
4 Landfills	L_0, k	V_{st0}	4475	4498
	V_{st0}, k	L_0	5428	5452
	V_{st0}, L_0	k	5392	5416
	k	V_{st0}, L_0	2934	2967
	L_0	V_{st0}, k	2007	2040
	V_{st0}	L_0, k	5299	5332
	none	**V_{st0}, L_0, k**	**1805**	**1853**
	V_{st0}, L_0, k	none	6497	6516
3 Landfills	L_0, k	V_{st0}	1789	1812
	V_{st0}, k	L_0	5134	5157
	V_{st0}, L_0	k	5063	5086
	k	**V_{st0}, L_0**	**1538**	**1571**
	L_0	V_{st0}, k	1639	1672
	V_{st0}	L_0, k	5022	5055
	none	V_{st0}, L_0, k	1343	1389
	V_{st0}, L_0, k	none	6085	6103

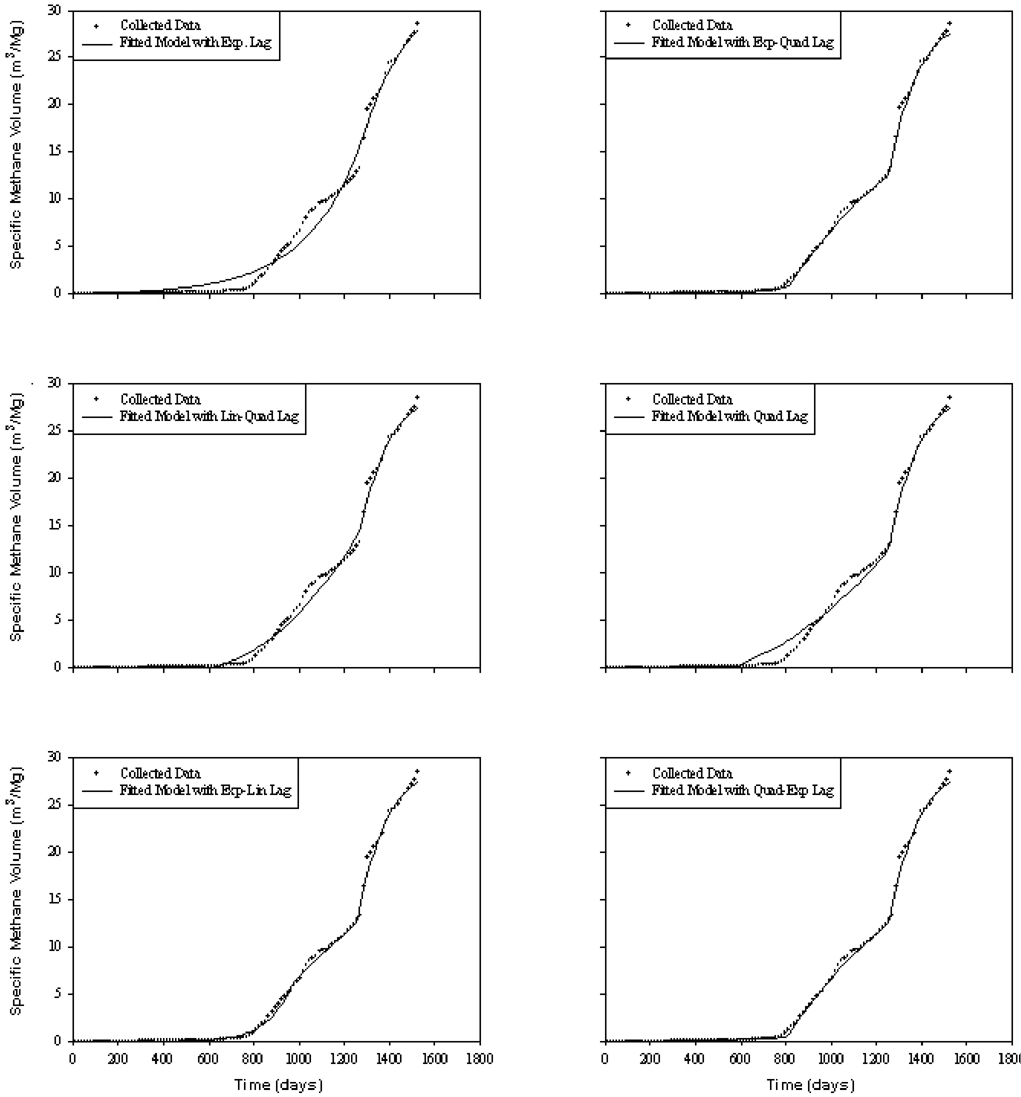

Figure A-1. Example of Data and Fitted Models with Various Lag Phase (Georgia Tech Dry Lysimeter Data).