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A study of settlement in landfills due to biodegradation

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ABSTRACT

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by
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Finding new space for landfills is difficult due to land availability, stringent environmental regulations, and public sentiment. So other means of waste disposal, such as hauling it to a distant landfill, or incinerating it, will have to be resorted to. These methods may be unpopular with the public involved. By studying settlement due to biodegradation, ways to increase settlement can be found, allowing for additional waste disposal capacity in operating, and closed landfills.

Existing theoretical models are based on rheological concepts, not on biodegradation. So, they do not realistically model settlement. In this study, a model to determine the rate, and magnitude of settlement due to biodegradation was formulated. The results of the model were then compared to those of existing theoretical models, and no correlation could be made. However, the settlement predicted by the proposed model did compare favorably with Sowers model which is based on field data. To verify the proposed model, an experiment was set up to measure settlement and gas generation in a waste sample.

A STUDY OF SETTLEMENT IN LANDFILLS DUE TO BIODEGRADATION

by
Michael Guasconi

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A Study of Settlement in Landfills due to Biodegradation

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LIST OF ABBREVIATIONS AND SYMBOLS

a = average amount of gas produced per year for T
b = secondary compressibility factor
$c_{\alpha\epsilon}$ = secondary compression ratio
e = void ratio of the waste
G_S = specific gravity of the waste
h = height of refuse
h_P = height of refuse after primary compression
k = a constant
M = settlement in feet per month
m = refuse compressibility
NIMBY = Not In My Back Yard
NJIT = New Jersey Institute of Technology
n = rate of compression
S = settlement
S_S = settlement due to secondary compression
t = time period of total gas production
T = time period of phase one
t_C = construction period (months)
t_e = elapsed time since start of fill construction (months)
t_m = median fill age (months)
t_P = time for primary consolidation to occur
t_r = reference time to make time dimensionless (1 day, 1 year, etc.)
t' = time since load application
t* = time since landfill closure
V = the total volume of gas produced per cubic foot of waste
V′ = gas production (ft^3 gas/ft^3 waste/ year)
w = moisture content
W.C. = Well Compacted
δ_{Waste} = unit weight of the waste
δ_W = unit weight of water
ε = strain
$\Delta\varepsilon$ = change in strain
$\Delta\sigma$ = compressive stress
λ/b = rate of secondary compression

CHAPTER 1

INTRODUCTION

Sanitary landfilling of municipal solid waste has been utilized since the 1940's in the United States with its advent in New York City (Tchobanoglous, Theisen and Vigil 1993). With the rapid growth of metropolitan areas since the 1960's, many landfills are either near their design capacity or have reached their capacity and closed. Increasingly stringent environmental regulations, NIMBY (Not in my backyard) syndrome of the public, and the lack of available land, make new landfills expensive. So, municipal solid waste must either be shipped long distances to other landfills, or incinerated. These disposal options are very unpopular, expensive, and non viable. So, there exists a need for finding additional landfill capacity.

One of the ways to find additional landfill capacity is to accelerate the ongoing settlement in existing landfills. These landfills are presently undergoing biodegradation, a time dependent, and time consuming process. As these chemical changes take place, volume changes occur, causing settlement in the landfill. Available techniques do not predict the mechanisms causing settlement, especially due to biodegradation. By studying how biodegradation affects landfill settlement, final settlement values can be predicted, and ways to increase the rate of settlement can be found. This will allow for closed landfills to operate again, and the life of existing landfills to be extended beyond their predicted closure times. The capacity of the landfill can be increased since the faster the rate of settlement, the more volume of waste that can be disposed of in the same amount of landfill area.

In this study, a model was formulated to determine the rate, and magnitude of settlement due to biodegradation. For a given composition of municipal waste, a gas generation scheme was developed utilizing mass balance techniques. Some of the ideas presented by Disbrow (1988), and Arntz (1993) to calculate volume changes due to biodegradation, and settlement were incorporated in this study. Computations were performed to determine settlements as function of time. The results of this study were compared, and correlated with the existing theoretical models. It was noted that the model predicted settlement values that compared favorably with those of Sowers model, which is based on field data. In order to verify the gas generation model utilized for this study, an experimental setup was constructed in the laboratory. A mixture to simulate the various ingredients of municipal waste in landfill was prepared, and placed in the biodegradation apparatus. Provisions were made in the apparatus to measure secondary settlement and gas generation.

CHAPTER 2

LITERATURE REVIEW

Almost all of the existing models for secondary settlement of landfills are based on the theory of creep. The rheological models that utilize stress-strain-time relationships will be reviewed at first. Some of the models are empirical based on actual time-settlement data. These models will also be presented. Then models based on biodegradation will be discussed.

2.1 Rheological Models Based on Secondary Consolidation

2.1.1 Gibson and Lo Model

Edil, Ranguette, and Wueller (1990) proposed that the Gibson and Lo model used for the secondary compression of certain soils can also be used for landfill settlement. This model is a rheological model that uses springs and dashpots to predict secondary settlement. The spring and dashpot constants for this model are based on studies made at four different landfill sites. In this model, the secondary settlement is computed from Equation 2.1 below.

$$S_S = h\varepsilon = h\,\Delta\sigma\,\{b\,(1 - \exp^{[-(\lambda/b)\,t']})\} \qquad (2.1)$$

Where

S_S = settlement due to secondary compression (feet);

h = height of refuse (feet);

ε = strain;

b = secondary compressibility factor (kPa^{-1});

$\Delta\sigma$ = compressive stress (kPa);

λ/b = rate of secondary compression (day^{-1});

t' = time since load application (days).

It is believed (Raghu, 1995) that most of the secondary settlement occurring in a landfill is due to the biodegradation of the solid waste. This phenomenon results in the phase transformation of waste from a solid, to liquid and gas, resulting in settlement. So, the secondary settlement is a chemical phenomenon, and not a rheological process. Thus, it is felt that the Gibson and Lo model does not physically model what is occurring in the landfill. This makes it is difficult to visualize the process, making the choice of suitable values for the parameters for this model such as the spring constants, and damping coefficients very difficult. Moreover, it is believed that the applied compressive stress, a parameter in this model, does not influence biodegradation considerably. Wall and Zeiss (1995) found that this model, and the power creep law did not predict settlement accurately, and did not include them in their study.

The parameters presented by Edil, et al., (1990) for the secondary compressibility factor, and the rate of secondary compression are presented in terms of a trend curve. This curve gives a wide range of values for the above parameters. Settlements computed with these parameters are in the range of one to two orders of magnitude. This makes the choice of the parameters difficult. An example of computations of settlement utilizing this model will be presented later.

2.1.2 Power Creep Law

Edil, Ranguette, and Wueller (1990) also proposed that the power creep law can be used for predicting settlement in a landfill. This law represents a relationship for time dependent deformation under constant stress. Formula based on this law is presented in Equation (2.2).

$$S = h\varepsilon = h\, \Delta\sigma\, m\, (t'/t_r)^n \qquad (2.2)$$

Where,

S = settlement (feet);

t_r = reference time to make time dimensionless (1 day, 1 year, etc.);

m = refuse compressibility (kPa^{-1})

n = rate of compression.

Typical recommended average values for "m" and "n" are $2.5(10^{-5})$ 1/Kpa, and 0.65 respectively.

This model is based on the Gibson an Lo model. Hence, it suffers from the same limitations as the Gibson and Lo model, presented in the earlier section of this study.

2.1.3 Sites From Which Data Was Obtained For Rheological Models

Data from four sites was utilized to arrive at the parameters used for the rheological models. One of the sites included was a 40-50 year old town dump that was excavated, and relocated to a new site. After 40-50 years, almost all of the biodegradation of the waste would have been complete (Disbrow 1988, Arntz 1993) along with the accompanying settlement. The settlement values obtained from this site would not be representative of secondary settlement. Thus, this data may not be valid to use. Another site that was studied consisted of constructed experimental cells. The age of the refuse was not mentioned, so it is not known if settlement due to biodegradation had occurred or not.

The third site included in this study was a landfill that had a leachate level of 7.6 meters (24.9 feet) above the base of the landfill. In New Jersey, the applicable law stipulates that no more than 1 foot of head of leachate can act upon the liner [NJAC 7:26-2A.6 (2d)], and similar regulations exist for other states, and at the federal level. This site is an old landfill that is not in compliance with existing regulations, and may not be appropriate to use in calculating the parameters for the models.

A unit weight of refuse of 10.7 kN/m^3 (67.5 lbs/ft^3) was used for all the four sites in determining the parameters for the secondary compressibility factor, and the rate of secondary compression. While this unit weight falls between the values given by Oweis and Khera (1990) for landfills with leachate mounds, it is too high to be used for the other three sites. It will be shown later in this report that the unit weight of waste used for this study is 32.68 lbs/ft^3, while Oweis and Khera (1990) give a typical value of 35 lbs/ft^3 (5.5 kN/m^3) for domestic municipal waste, and 40 lbs/ft^3 (6.28 kN/m^3) for mixed municipal and industrial waste. A unit weight such as 10.7 kN/m^3 (67.5 lbs/ft^3) is possible only for wastes containing large quantities of inorganic materials such as construction debris. If this is the case, then biodegradation would be minimal since there would not be enough organic material to support the process of biodegradation. So it is felt that the data utilized for verifying the rheological models is not truly representative. Thus these models have limited use.

2.2 Models Based on Field Measurements

The second type of models are based on field measurements. Yen and Scanlon model (1975), and Sowers model (1973) are models belonging to this category that will be discussed.

2.2.1 Yen and Scanlon Model

The Yen and Scanlon model (1975) for landfill settlement is an empirical one based on a study of a period of up to nine years of settlement data from three landfills in the Los Angeles County Sanitation District. Settlement trends for the log of the median fill age in months versus the settlement rate per month were plotted, and an equation based on the trend was formulated.

For a forty to eighty foot high landfill, the equation is as follows.

$$M = 0.088 - [0.038 \log (t_m)] \tag{2.3}$$

Where,

M = settlement in feet per month;

t_e = elapsed time since start of fill construction (months);

t_C = construction period (months);

t_m = median fill age (months) where $t_m = t_e - t_C/2$.

Settlement values computed from this model beyond certain time periods were found to be negative. Hence this model does not predict reliable values of settlement. Details demonstrating the limitations of this model will be presented later in this thesis.

2.2.2 Sowers Model

The Sowers model was one of the first models developed to predict the secondary settlement of waste in a landfill. According to Wall and Zeiss (1995), Sowers attributes secondary settlement of waste to the combination of mechanical secondary compression, physicochemical action, and biochemical decay. The model is a modified form of Buisman's theory of secondary compression of soils which assumes that the secondary portion of the settlement curve is linear with respect to time (Wall and Zeiss, 1995). The computation of settlement is based on the equation given below.

$$S_S = h_P \, c_{\alpha e} \log \left(t^*/t_P \right) \qquad (2.4)$$

Where,

h_P = height of refuse after primary compression (feet);

$c_{\alpha e}$ = secondary compression ratio;

t^* = time since landfill closure (years);

t_P = time for primary consolidation to occur (years).

Based on field measurements, Sowers (1973) recommends values of the secondary compression ratio (slope of the settlement vs. log time plot) for a void ratio of 3 as being in the range of 0.02 to 0.07. The value of 0.02 corresponds to conditions in the landfill unfavorable to biodegradation, while a value of 0.07 corresponds to favorable conditions for biodegradation. Sowers (1973) also gave an equation to calculate the secondary compression ratio as a function of the void ratio for the waste. This equation is as follows.

$$c_{\alpha e} = (0.03 \text{ to } 0.09)e \,/\, (1+e) \qquad (2.5)$$

Where "e" is the void ratio of the waste.

The range of values of 0.03 to 0.09 corresponds to whether conditions in the landfills are favorable or unfavorable to biodegradation. A complete discussion of this model versus the model proposed in this study (NJIT model), will be presented in later chapters of this thesis.

2.3 Models Based on the Biodegradation Process

Most settlement occurring in landfills is believed to be due to biodegradation. Research in NJIT is aimed at developing models based on gas production resulting from biodegradation.

2.3.1 Disbrow Version of NJIT Model

Disbrow (1988) proposed that a link existed between the rate of gas production, the resulting loss of volume, and the secondary settlement due to biodegradation in a landfill. He tried to predict settlement by calibrating a separate equation based on the rate of settlement being an inverse exponential function of time (similar to the gas production model) from limited information gathered from an actual landfill. Disbrow did make some comparisons between his predicted values, Sowers model, and actual field measurements. He proposed that a refinement of the models was necessary, and that a study into mass balance equations, and the mechanisms involved be studied.

2.3.2 Arntz Version of NJIT Model

Arntz (1993), following the work of Disbrow, refined the NJIT model by basing settlement due to biodegradation on the volume change of a landfill resulting from gas production. This was based on the predicted percent decomposition of the waste that would occur. He also used a mass balance approach to determine the chemical composition of the waste to arrive at the volume of gas produced. Arntz also made some limited comparisons between his predicted settlement values, Sowers values, and actual field measurements.

More study of Arntz's and Disbrow's models was necessary since the results these models were not correlated with already existing models in terms of settlement. They also did not make any comparisons between the secondary compression ratio values predicted by their versions of NJIT model, and already established values for the secondary compression ratio from other models.

CHAPTER 3

PROCESSES INVOLVING BIODEGRADATION AND GAS GENERATION

In this chapter, a brief explanation of the biodegradation and gas generation process will be presented for background purposes. A more detailed explanation of these processes can be found elsewhere (Tchobanoglous, et al., 1993).

3.1 Biodegradation

Biodegradation is the process by which microorganisms degrade the complex organic compounds into simple compounds and gas. The gaseous components consist of mostly Methane (CH_4), and Carbon Dioxide (CO_2), with smaller amounts of Hydrogen (H_2), Nitrogen (N_2), Hydrogen Sulfide (H_2S) and, Oxygen (O_2). Municipal waste is composed of almost 80 percent by weight organic matter (Tchobanoglous, et al., 1993). So, significant quantities of gas can be generated depending on the environmental conditions in the landfill. The rate of decomposition depends on the type of waste, and the ambient anaerobic conditions which include temperature, water content, and alkalinity. If the water content is too low, or the temperature is not supportive of the microorganisms, this will impede their ability to degrade the waste. Also, not all waste is easy to degrade. While up to 82 percent of food waste may be biodegradable, only 22 percent of a newspaper may biodegrade (Tchobanoglous, et al., 1993). On an average Tchobanoglous, et al., (1993) predict that approximately 19.7 percent of the solid waste will be converted to gas, with this value varying depending on site conditions. For the purpose of this study, 19.7 percent was utilized. The process of biodegradation, and the subsequent gas production can be significant for up to 40 years after the landfill is constructed (Disbrow 1988, Arntz 1993).

3.2 Gas Generation

Gas generation in a landfill is believed to occur in five phases (Tchobanoglous, et al., 1993). A summary of these five phases is as follows. The first phase, or initial adjustment phase occurs just after the waste is placed in the landfill. Microorganisms from the daily soil cover start to degrade the waste in an aerobic process since air becomes trapped with the waste. Gas composition during this phase consists of 80 percent N_2, and 20 percent O_2, by volume.

Once the Oxygen is depleted, phase two, the transition phase occurs. The aerobic degradation ceases, and anaerobic conditions develop. The amount of N_2, and O_2 generated begins to decrease, while the amount of CO_2 and H_2 increases.

In Phase three, the acid phase, the microbial activity of phase two accelerates, producing large volumes of CO_2 with lesser volumes of H_2. Acetic Acid is also produced by the microorganisms in large quantities. This is due to the microorganisms breaking down the organic waste into more suitable forms of energy for their needs.

In phase four, the Methane fermentation phase, a new group of microorganisms become dominant. These microorganisms, known as Methogens produce CO_2, and CH_4 from the Acetic Acid, and H_2 gas produced in phase three. During this phase, both the Methane gas formation, and Acetic Acid formation occur at the same time, but with the rate of acid formation reduced from that occurring earlier. The composition of the gas by volume is approximately 55 percent CH_4, and 45 percent CO_2. This process will continue until all of the biodegradable material is used up, and phase five, the maturation phase occurs. In this phase the CO_2, and CH_4 production drops off significantly since very little waste is left that can be decomposed.

CHAPTER 4

MODEL AND LABORATORY EXPERIMENT SET UP DEVELOPED FOR THIS STUDY

4.1 Model Developed For This Study

The NJIT gas production model used for this study is based upon the Simcon model first proposed by C.S. Holling at the University of British Columbia (Baron, et al., 1981). In this model a two phase system is used to represent gas production. The first phase of gas production is represented by a zero order mathematical equation, presented below, which increases linearly with time.

$$V' = aT \qquad (0 \leq t \leq T) \tag{4.1}$$

Where,

V' = gas production (ft^3 gas/ft^3 waste/ year);

a = average amount of gas produced per year for T;

T = time period of phase one.

The second phase of this model is represented by a first order mathematical model which is an inverse exponential function of time. Equation 4.2 represents this phase.

$$V' = aT \exp^{[-k(t-T)]} \quad (t \geq T) \tag{4.2}$$

Where,

t = time period of total gas production;

k = a constant.

This model assumes that gas generated by the biodegradation of the waste will be collected by the venting system of the landfill. By integrating the above equations with respect to time, the area under the curve can be found. The area under the curve represents the total gas production in cubic feet on a per cubic foot of disposed waste basis. The equation for the area under the curve is as follows.

$$V = aT^2 / 2 + (aT / b)(1 - \exp^{[-k(t-T)]}) \qquad (4.3)$$

Where "V" is the total volume of gas produced per cubic foot of waste. Details of the integration steps are located in Appendix A.

For the purpose of this study, the first phase of gas production is assumed to occur over a period of 10 years (after landfilling has commenced), while the second phase is assumed to occur over a 30 year period. These parameters can be modified depending on actual landfill conditions. Disbrow (1988) proposed that Equation 4.3 be somewhat modified. He proposed that 90 percent of the total gas production takes place over the 40 year period. The other 10 percent of gas production will occur over an unknown time period after the first 40 years. At first, he assumed that 99 percent of gas production would occur over the first 40 years, but found this not to be valid. The author believes that Disbrow's value of 90 percent was too low, and used a value of 95 percent. This value depends on how well the gas venting system is designed. For this study, good gas venting was assumed, resulting in minimal losses. This was not necessarily the case for Disbrow's study. Disbrow also found that the value of the constant "k" is equal to 0.076753. The constant "k" was determined by assuming that the rate of gas production at the end of the second phase to be equal to 0.1 of that at the first phase.

4.2 Gas Generation From Mass Balance Approach

To calculate the amount of gas being generated by the biodegradation of the waste, the composition of the waste being disposed of must be known. Ideally, actual waste samples should be analyzed for their chemical composition, but this was not possible. So a mass balance approach was utilized. A summary of the procedure followed is presented, with full details found in the work of Arntz (1993) and Tchobanoglous, et al., (1993). Appendix B presents the results of the procedure followed.

First, in computing the mass balance, the unit weight of the refuse is determined. Tchobanoglous, et al., (1993) presents information on the characteristics of a typical municipal waste. This data is presented in Table 4.1. From this information, the unit weight of the waste can be determined. A well compacted unit weight of 32.68 lbs/ft^3 was determined. This value is close to the value published by Oweis and Khera (1990) of 35 lbs/ft^3 for a typical municipal landfill.

Utilizing the data presented in Table 4.1 concerning the percent composition, and the moisture content of the waste components, the dry weight of the waste can be calculated. To simplify calculations, 100 lbs of waste was assumed. Tchobanoglous, et al., (1993) provides information to determine the chemical composition of the waste on a dry weight basis. This information is presented in Table 4.2.

TABLE 4.1 Typical Physical Composition of Municipal Solid Waste

Waste Type	Percent by Weight	Uncompacted Unit Weight (lbs/ft^3)	Compaction Factor	Moisture Content (percent)
Organic Component				
Food Waste	9	18	0.33	70
Paper	34	4	0.15	6
Cardboard	6	4	0.18	5
Plastic	7	4	0.1	2
Textiles	2	4	0.15	10
Rubber	0.5	9	0.3	2
Leather	0.5	9	0.3	10
Yard Waste	18.5	7	0.2	60
Wood	2	15	0.3	20
Inorganic Component				
Glass	8	12	0.4	2
Tin Cans	6	12	0.15	3
Aluminum	0.5	12	0.15	2
Other Metal	3	12	0.3	3
Dirt, Ash, Etc.	3	30	0.75	8

TABLE 4.2 Chemical Composition of the Waste: Percent by Weight (Dry Basis)

Component	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Organic						
Food Waste	48.0	6.4	37.6	2.6	0.4	5.0
Paper	43.5	6.0	44.0	0.3	0.2	6.0
Cardboard	44.0	5.9	44.6	0.3	0.2	5.0
Plastic	60.0	7.2	22.8	-	-	10.0
Textiles	55.0	6.6	31.2	4.6	0.15	2.5
Rubber	78.0	10.0	-	2.0	-	10.0
Leather	60.0	8.0	11.6	10.0	0.4	10.0
Yard Waste	47.8	6.0	38.0	3.4	0.3	4.5
Wood	49.5	6.0	42.7	0.2	0.1	1.5
Inorganic						
Glass	0.5	0.1	0.4	-	-	96.9
Metals	4.5	0.6	4.3	-	-	90.5
Dirt, Ash, Etc.	26.3	3.0	2.0	0.5	0.2	98.0

As shown above, the primary chemical components of the waste are Carbon, Hydrogen, Oxygen, Nitrogen, Sulfur, and, Ash. A summation of the dry weight of each of these chemical components is made, and then the organic components are converted into moles. Using a mole ratio of one for Nitrogen, the normalized mole ratios are computed, and the chemical equation of the waste, shown below, was determined.

$$C_{56.33}\ H_{88.31}\ O_{35.44}\ N \qquad (4.4)$$

Once the chemical equation of the waste is found, either by the mass balance method or by a chemical analysis, the total volume of gas that can be produced can be calculated. The following equation provided by Tchobanoglous, et al., (1993) is used to determine the total amount of gas generated.

$$C_A\ H_B\ O_C\ N_D + [(4A\text{-}B\text{-}2C\text{-}3D)/4]\ H_2O \Rightarrow$$

$$(4A+B\text{-}2C\text{-}3D)/8]\ CH_4 + [(4a\text{-}B +2C +3D)/8]\ CO_2 + NH_3 \qquad (4.5)$$

The values of A, B, C, and, D depend on the chemical equation of the waste. From equation 4.4, the calculated values are A=56.33, B=88.31, C=35.44, and D=1. With these values, the total amounts of Methane, and Carbon Dioxide generated per cubic foot of decompostable waste can be estimated. Based on the unit weight of the waste computed earlier, and the information on the moisture content of the of waste components, the dry unit weight of the waste can be calculated. The dry weight is then multiplied by 0.197 to arrive at the weight of gas produced per cubic foot of waste. By taking the ratio of the formula mass of the individual gas, to the total formula mass for Equation 4.4, and multiplying this by the total weight of gas mentioned above, the individual weights of Methane and Carbon Dioxide can be found. Dividing these weights by a value of 0.0447 lb/ft^3 for Methane, and 0.1235 lb/ft^3 for Carbon Dioxide, the total volume of these gases per cubic foot of waste can be calculated. For this study, a value of 40.4 ft^3 of Methane, and 35.38 ft^3 of Carbon Dioxide was determined. It was assumed that 100 percent of the gas generated was comprised of Methane, and Carbon Dioxide. A total value of 75.78 ft^3 of gas per ft^3 of waste is computed, which is the area under the gas generation curve represented by Equation 4.3. A plot of the gas generation curve for the NJIT model is presented in Figure 4.1.

Once the total value of gas generated is found, the value of "a" for the NJIT equation can be computed. This is done by setting "V" equal to the product of 0.95, and the total gas produced, as discussed earlier. The value of "a" was computed to be 0.43 for this study. Details of the calculations for "a" are in Appendix C.

4.3 Settlement Calculations

In calculating the settlement of the landfill, it was assumed that volumetric strain is equal to the vertical strain. This is valid if the thickness of the landfill is considered to be quite small compared to its length and width. Since 19.7 percent of the volume of solid waste was considered to be converted into gas (biodegradable), this would correspond to 19.7 feet of settlement occurring in a 100 foot high landfill. These estimates agree with those of Coduto and Huitric (1990), who state that the settlement due to biodegradation is probably between 18 percent to 24 percent of the refuse thickness.

For this study, a landfill height of 40 feet was assumed. Volumetric strain occurring in a landfill for a particular year is calculated by dividing the area under the gas generation curve in a particular year by the total area under the curve. To calculate the

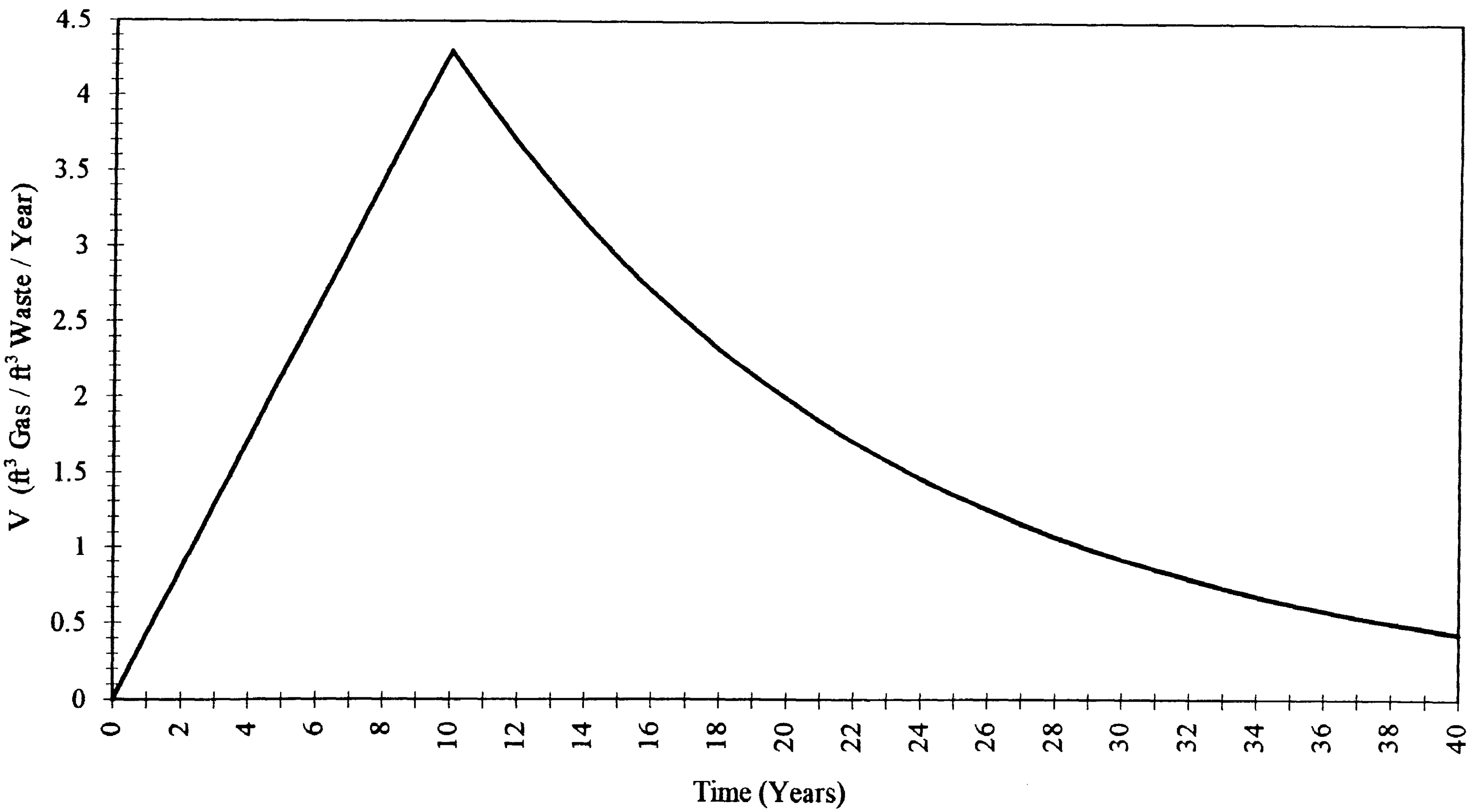

Figure 4.1 Gas Production Curve for the NJIT Model

settlement, an Eulerian system of coordinates was used. In other words, settlement for the following year was computed as a percentage of the height of the landfill during the previous year, and not on the original height of the landfill. This is due to the fact that the magnitudes of settlements result in appreciable changes in geometry of the landfill. Details of these calculations can be found in Appendix C. The results of these calculations, and the discussion of these results will be presented in next chapter.

4.4 Experimental Set Up

As part of this study, a laboratory experiment was set up to verify the results of the NJIT model. Since actual waste samples destined for a landfill were unavailable at the time of the experiment, a representative waste sample was created in the laboratory. The composition of this sample was the same as that presented in Table 4.1. Leather was omitted from the mixture since none was available at the time of the experiment.

A landfill test cell 11 3/4 inches high having an inner diameter of 6 1/4 inches was used. The cell design allowed for the collection of both gas and leachate generated by biodegradation. Measurements of settlement can be made by reading a scale that is attached to the cell. This cell is capped by a plunger sealed with an o-ring. This prevents both gas and moisture from escaping the cell.

A waste sample with a height of 10 inches, corresponding to a volume of 0.176 ft^3 was placed in the cell. This height of 10 inches allows enough room for a 1/2 inch layer of gravel to be placed on both the top, and bottom of the sample. This was done to prevent clogging of the Methane and leachate collection vents. Also, It allows for space so that the plunger may be placed on the cell properly.

Ideally, 5.75 lbs of waste, corresponding to a unit weight of 32.68 lbs/ft^3, should be placed in the cell. It was not possible to achieve this unit weight in the cell, so 3.62 lbs of waste, corresponding to a unit weight of 20.57 lbs/ft^3, was placed in the cell. An extra 0.33 lbs of moist soil from a field was added to the waste to introduce microorganisms so that biodegradation may occur. A dead load of 30.4 lbs was applied to the waste simulating approximately 6.92 feet of overburden waste over the cell.

Gas was vented from the cell to an Erlenmeyer flask which is used to collect any escaping moisture, and then to a gas collection bottle. This bottle contained Potassium Hydroxide liquid, and had a scale calibrated to the bottles volume that allowed for gas readings to be taken. Gas enters through the top of the bottle, displacing the liquid out of the bottom. This allows for the volume of gas, the difference between the liquid levels, to be read. The bottle is connected to another bottle at an equal height to the liquid, so the initial liquid levels between the bottles are equal. Once gas generation begins, it will collect the displaced liquid to allow for gas readings to be measured. Details of this setup are in Figure 4.2.

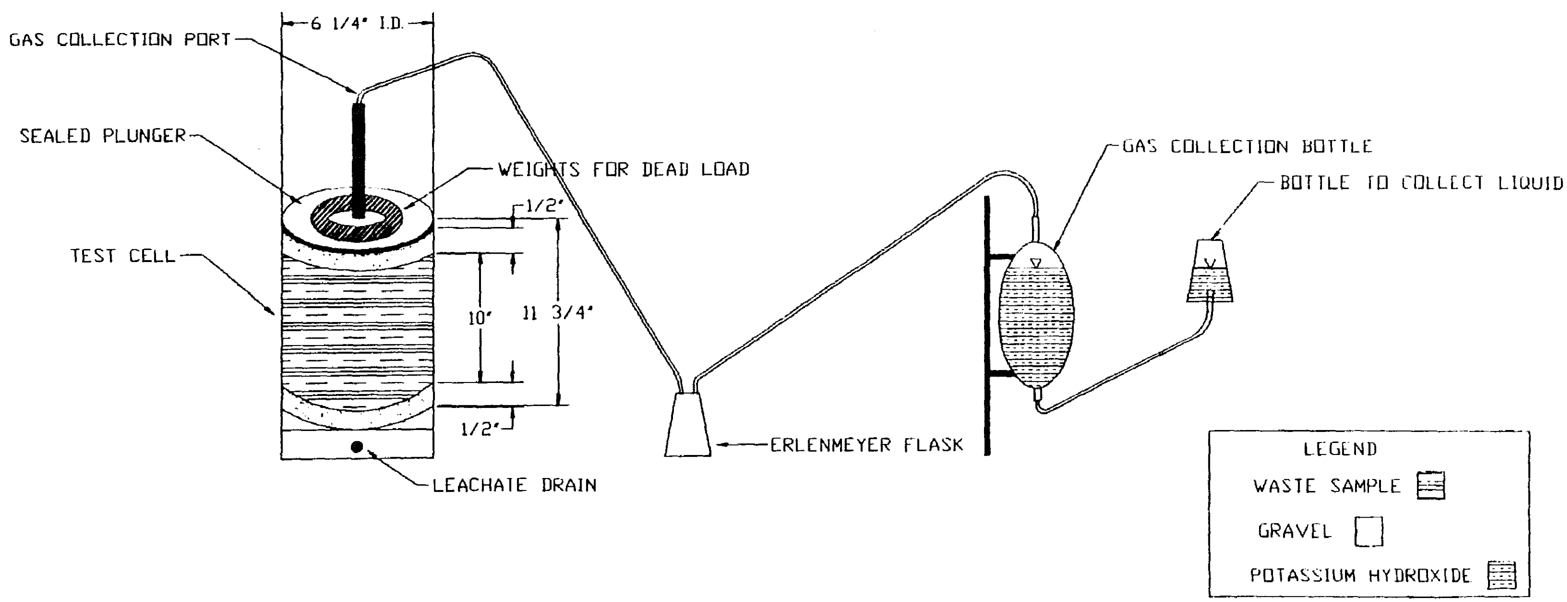

FIGURE 4.2 Details of Laboratory Set Up to Study Biodegradation

CHAPTER 5

SECONDARY SETTLEMENT COMPUTATIONS USING SEVERAL MODELS

Attempts were made to compute secondary settlements as functions of time utilizing the available models. Summary of these results are presented below with the details presented in Appendix A.

5.1 Yen and Scanlon Model

As mentioned earlier, computations based on the Yen and Scanlon model could not be utilized for this study. This is due to the fact that the model cannot predict settlements realistically beyond a certain time. In Equation 2.3, if M is set equal to zero, "t_C" set equal to 120 months (10 years), the time corresponding to zero settlement since fill construction can be calculated. The calculated value is 226.9 months (22.2 years). This says that all settlement in the landfill will cease after 22.2 years from the start of fill construction. But as mentioned earlier, settlement due to biodegradation can occur for up to 40 years or more. By setting "t_e" in Equation 2.3 equal to 480 months (40 years) with "t_C" still equal to 120 months, the settlement was found to be - 0.011 ft/month. This is not possible, thus this model cannot predict settlement of a landfill due to biodegradation.

5.2 Gibson and Lo Model

As with the Yen and Scanlon model, the results of Gibson and Lo model also could not be utilized for this study. One of the reasons was that the parameters for the model were presented as a trend curve with a wide range of limits. This curve is plotted over a range of applied compressive stress from 0 to 300 kPa. If a value of 100 kPa is chosen, the secondary compressibility factor has a range of 0.0006 to 0.003 kPa^{-1}. Assuming a value of 0.001 for the secondary compression rate factor, and setting t' equal to 14600 days (40 years), the calculated settlement values range from 2.4 ft. to 12.0 ft. This range is very wide. A wide range of values is also presented for the secondary compression rate factors. The range of the log average strain rate for this curve is between 0.1 to 50 day^{-1}. If a value of the average strain rate is assumed to be 10 day^{-1}, the range of the secondary compression rate factor is from 0.009 to 0.01 day^{-1}. The wide range of values presented for makes it difficult to choose suitable values for these parameters. So, the results of this model were not used in this study.

5.3 Sowers Model

As mentioned earlier, Sowers model of secondary compression was used for computing secondary settlements in this study. For this purpose, the operating life of this landfill was considered to be 10 years, with a fill height of 40 feet. The secondary settlement, and the corresponding fill height were computed for a period of time of 30 years after the landfill has ceased operations. Time for primary settlement to occur was assumed to be half an year. A value of the secondary compression ratio of 0.07 was used, corresponding to favorable conditions of biodegradation. An attempt was made to rationalize the choice of this value. Substituting a value of 2.0, the specific gravity of solids for organic soils, for the waste (since they both biodegrade), and using the calculated unit weight of 32.68 lbs/ft^3 with a moisture content value of 21.22 percent determined from Table 4.1, in Equation 5.1 below, the void ratio was determined to be 3.63.

$$\delta_{Waste} = [(G_S + wG_S)\delta_W] / (1+e) \qquad (5.1)$$

Where,

δ_{Waste} = unit weight of the waste (lbs/ft^3);

G_S = specific gravity of the waste;

w = moisture content;

δ_W = unit weight of water (lbs/ft^3).

For the typical waste sample used for this study, the secondary compression ratio was found to be 0.0705, just above Sowers value of 0.070 for favorable conditions of biodegradation. Since a void ratio of 3 was assumed by Sowers, the secondary compression ratio of 0.07, based on a void ratio of 3.63 is deemed to be acceptable.

Table 5.1 presents the results of the secondary settlement calculations. As shown, for 30 years after the landfill has closed, total secondary settlement was found to be 4.98 feet, corresponding to a fill height of 35.02 feet. Figure 5.1 shows a plot of secondary settlement vs time. Secondary settlement vs log time, the slope of which is "$c_{\alpha e}$", is plotted in Figure 5.2.

5.4 NJIT Model

The results of the NJIT model are presented in this section. Using Equation 4.3 with $0 \geq t \leq 40$ years, and T = 10 years, the total gas production values and corresponding settlement values can be calculated using the methodology presented before. Table 5.2 presents the values of gas production, settlement due to biodegradation and the total fill height. Full details of this work can be found in Appendix C. As shown, settlement due to biodegradation was found to be 6.91 feet corresponding to a fill height of 33.09 feet. A plot of settlement vs time for the NJIT model is presented in Figure 5.3. Figure 5.4

Table 5.1 Values of Secondary Settlement and Fill Height for Sowers Method

Time (years)	Time after Closure (years)	Secondary Settlement (ft.)	Fill Height (ft.)
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
10	0	0.00	40.00
11	1	0.84	39.16
12	2	1.69	38.31
13	3	2.18	37.82
14	4	2.53	37.47
15	5	2.80	37.20
16	6	3.02	36.98
17	7	3.21	36.79
18	8	3.37	36.63
19	9	3.51	36.49
20	10	3.64	36.36
21	11	3.76	36.24
22	12	3.86	36.14
23	13	3.96	36.04
24	14	4.05	35.95
25	15	4.14	35.86
26	16	4.21	35.79
27	17	4.29	35.71
28	18	4.36	35.64
29	19	4.42	35.58
30	20	4.49	35.51
31	21	4.55	35.45
32	22	4.60	35.40
33	23	4.66	35.34
34	24	4.71	35.29
35	25	4.76	35.24
36	26	4.80	35.20
37	27	4.85	35.15
38	28	4.89	35.11
39	29	4.94	35.06
40	30	4.98	35.02

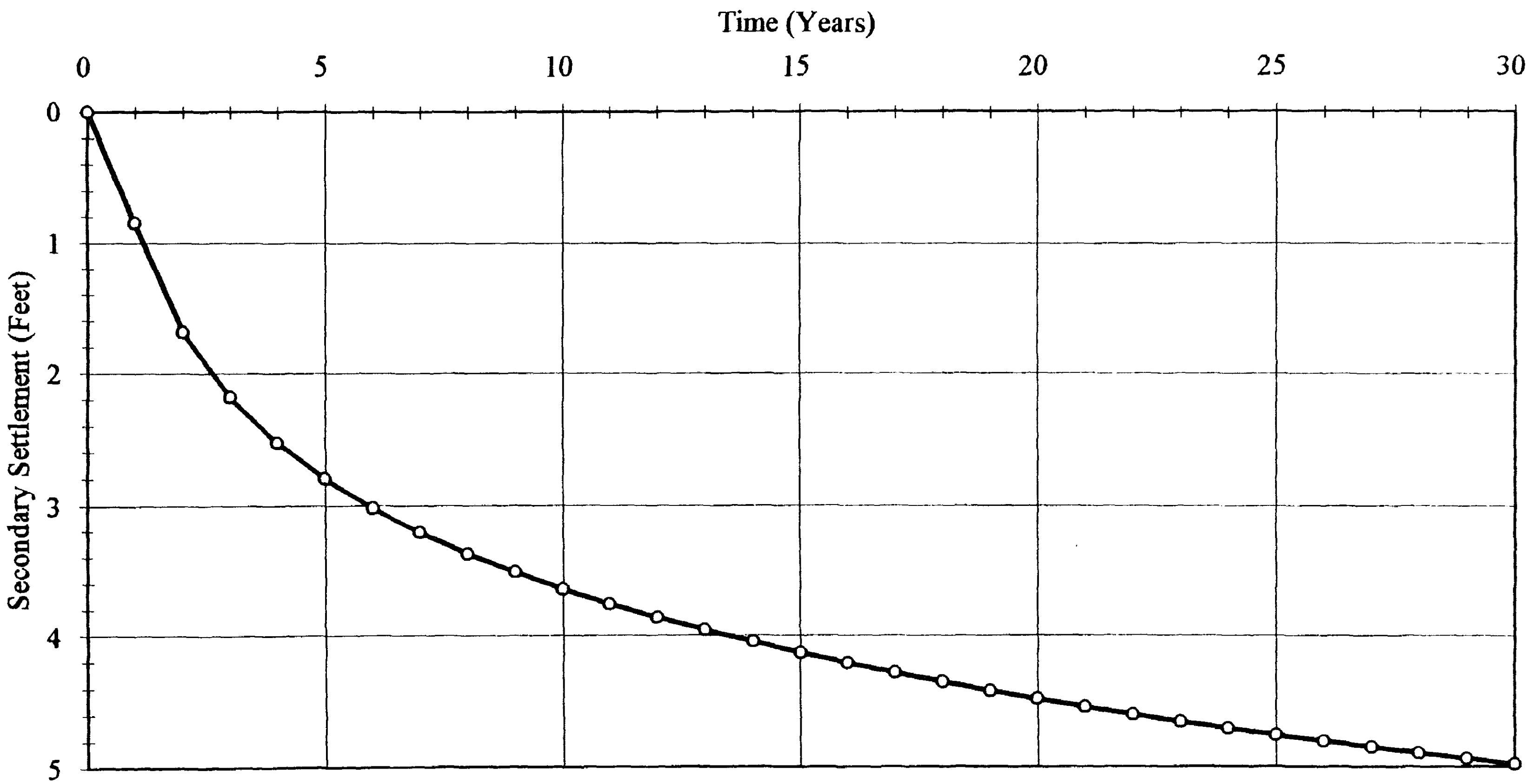

Figure 5.1 Secondary Settlement vs Time for Sowers Model

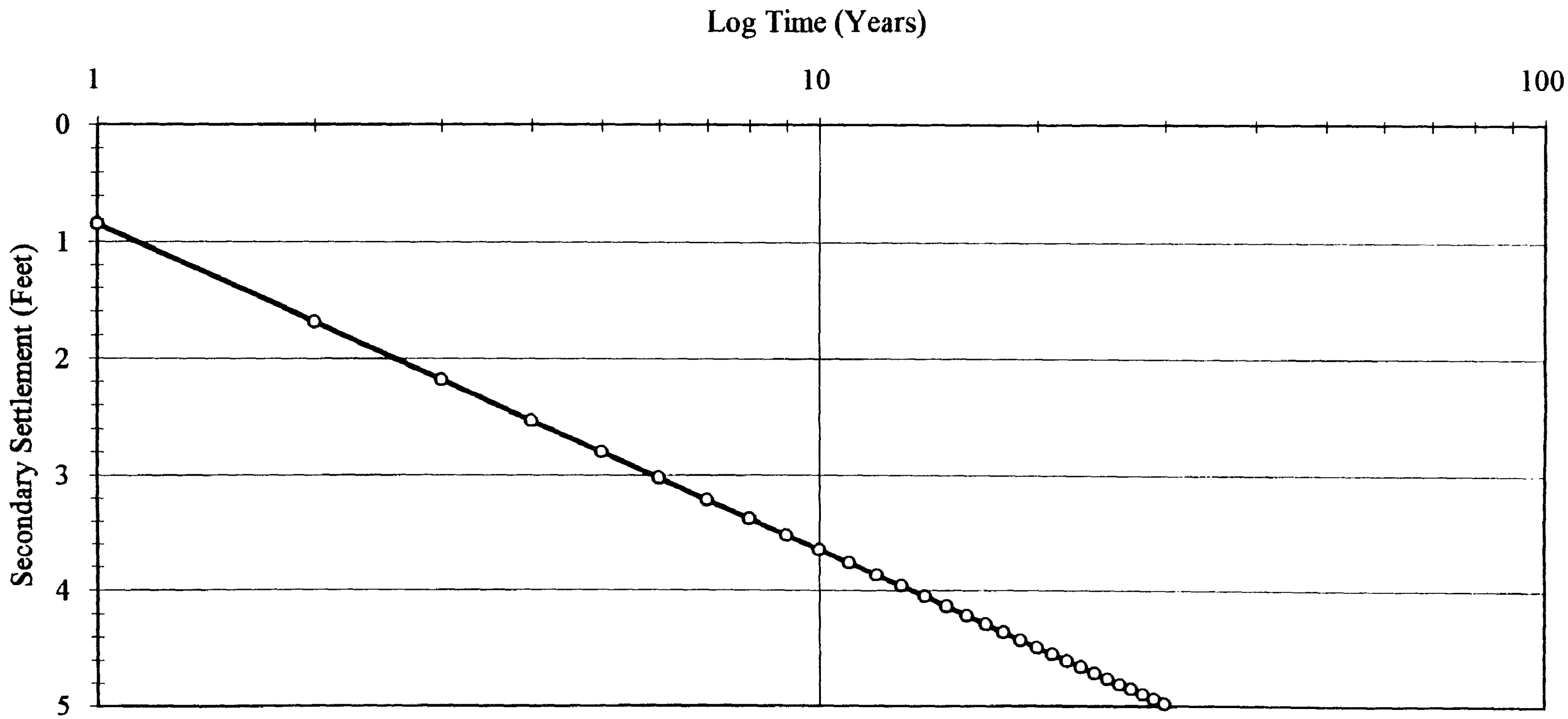

Figure 5.2 Secondary Settlement vs Log Time for Sowers Model

Table 5.2 Values of Gas Production, Settlement and Fill Height for the NJIT Model

Time (years)	Time after Closure (years)	Gas Production (ft^3 gas/ ft^3 waste)	Settlement due to Biodegradation (ft.)	Fill Height (ft.)
0		0.00		
1		0.22		
2		0.86		
3		1.94		
4		3.44		
5		5.38		
6		7.74		
7		10.54		
8		13.76		
9		17.42		
10	0	21.50	0.00	40.00
11	1	25.64	2.67	37.33
12	2	29.47	3.04	36.96
13	3	33.02	3.38	36.62
14	4	36.31	3.69	36.31
15	5	39.36	3.98	36.02
16	6	42.18	4.24	35.76
17	7	44.79	4.49	35.51
18	8	47.21	4.71	35.29
19	9	49.45	4.92	35.08
20	10	51.53	5.10	34.90
21	11	53.45	5.28	34.72
22	12	55.23	5.44	34.56
23	13	56.88	5.59	34.41
24	14	58.40	5.72	34.28
25	15	59.82	5.85	34.15
26	16	61.13	5.97	34.03
27	17	62.34	6.07	33.93
28	18	63.46	6.17	33.83
29	19	64.50	6.26	33.74
30	20	65.47	6.35	33.65
31	21	66.36	6.43	33.57
32	22	67.19	6.50	33.50
33	23	67.95	6.57	33.43
34	24	68.66	6.63	33.37
35	25	69.32	6.68	33.32
36	26	69.93	6.74	33.26
37	27	70.49	6.79	33.21
38	28	71.01	6.83	33.17
39	29	71.49	6.87	33.13
40	30	71.94	6.91	33.09

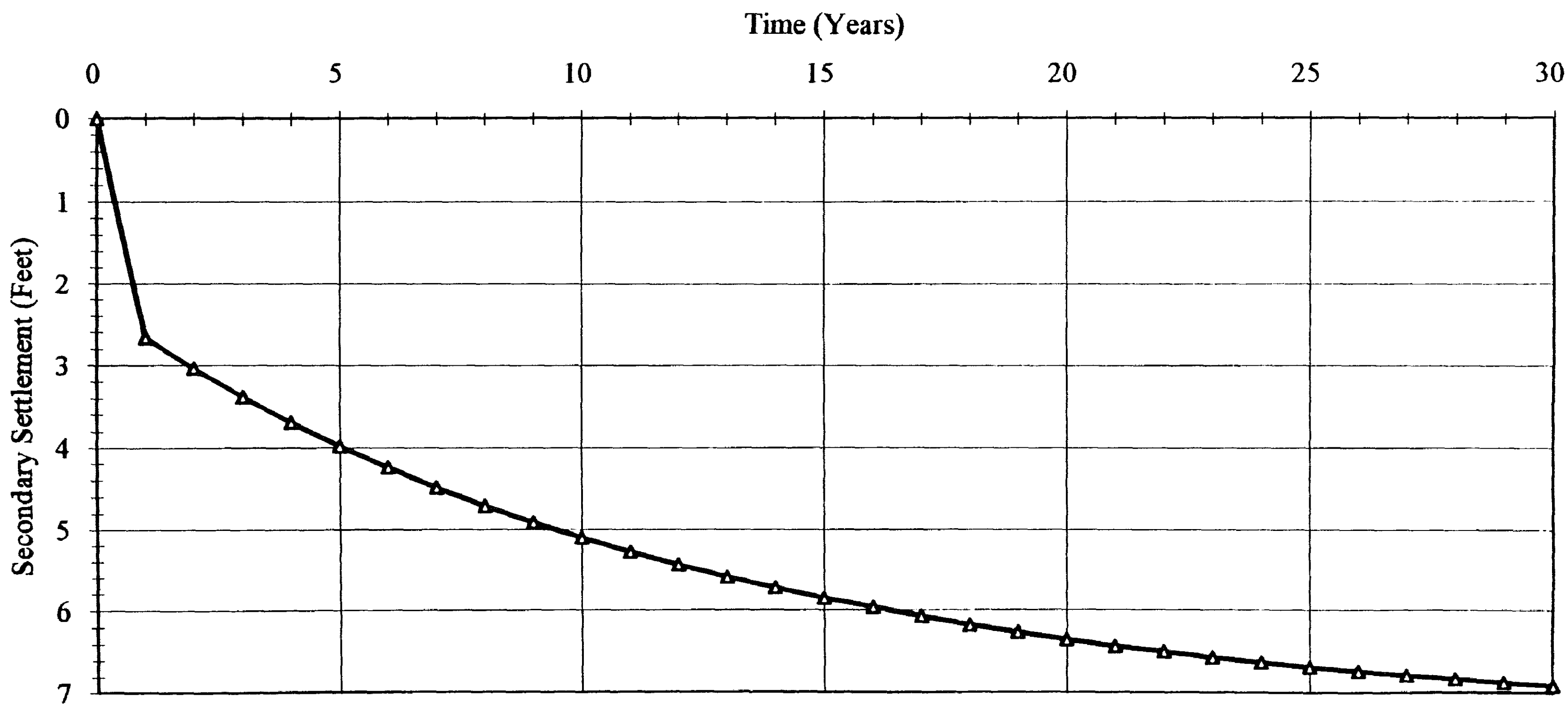

Figure 5.3 Plot of Secondary Settlement vs Time for the NJIT Model

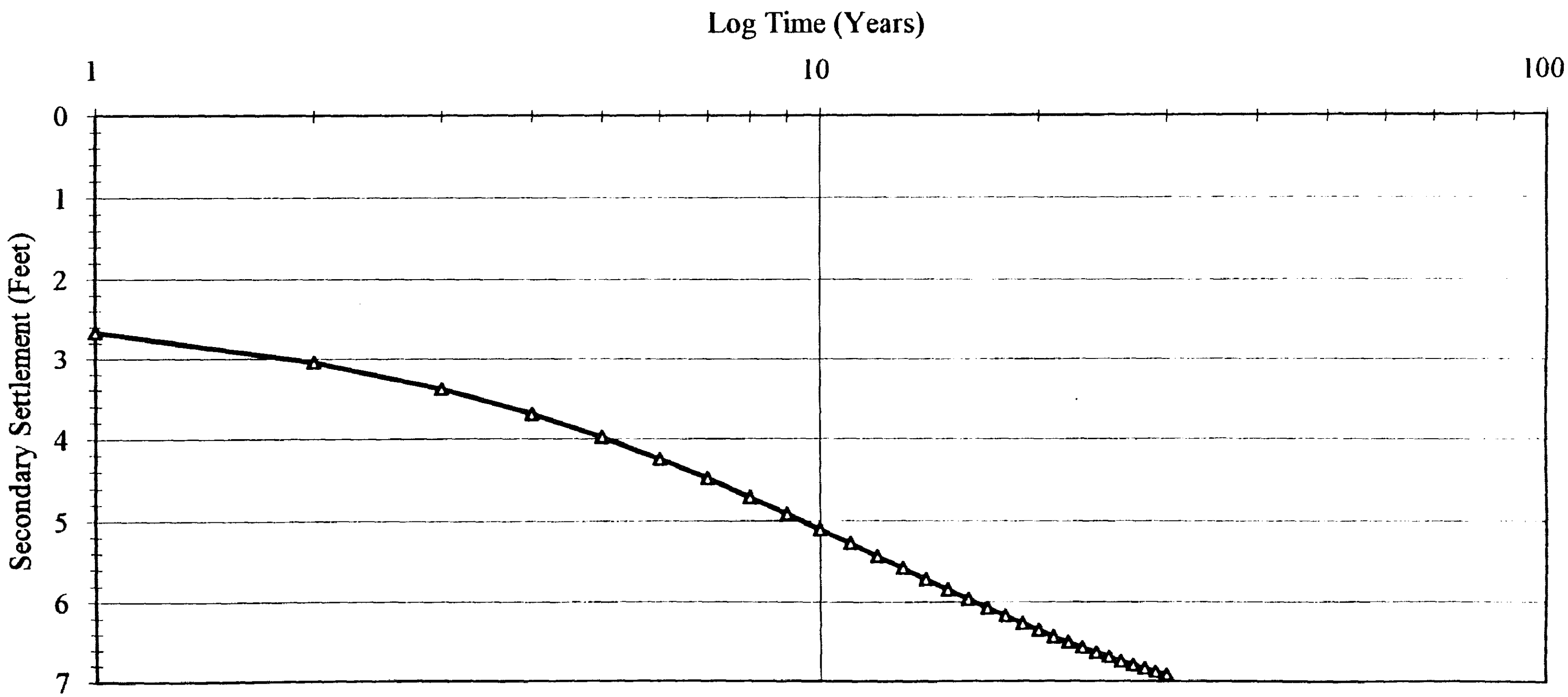

Figure 5.4 Plot of Secondary Settlement vs Log Time for the NJIT Model

presents a plot of settlement vs log time for this model.

The secondary compression ratio can be found in a variety of ways. If settlement is considered linear vs. log of time, as with the Sowers model, a line can be plotted between the upper and lower values of the calculated settlement range. This line, denoted as line 1 on Figure 5.5 has a slope of 0.071, which is the secondary compression ratio.

It is the authors belief that "$c_{\alpha\epsilon}$" is not linear over the log of time as with the Sowers model, but varies over time. To account for this, it is felt that two separate "$c_{\alpha\epsilon}$" values occur over time. A line tangent to the two phase of the settlement vs log time curve can be plotted, and the values of the secondary compression ratio found. This can be seen in Figure 5.6. In this figure, tangent line 2 represents the first 3 3/4 years of settlement due to biodegradation, and has a slope of 0.033, while tangent line 3, representing the remaining 26 1/4 years of settlement due to biodegradation has a slope of 0.097. This will be discussed further in chapter 6.

5.5 Laboratory Experiment

The results from the laboratory experiment are inconclusive. While 11/16 of an inch of settlement due to primary consolidation was observed, no settlement due to biodegradation was noted. The author attributes this due to the limited time available for the study. The time frame allotted for the completion of the study was not long enough to make any noticeable observations on settlement and biodegradation. The experiment is still in progress, and it is expected that long term data from this study will be gathered by other researchers.

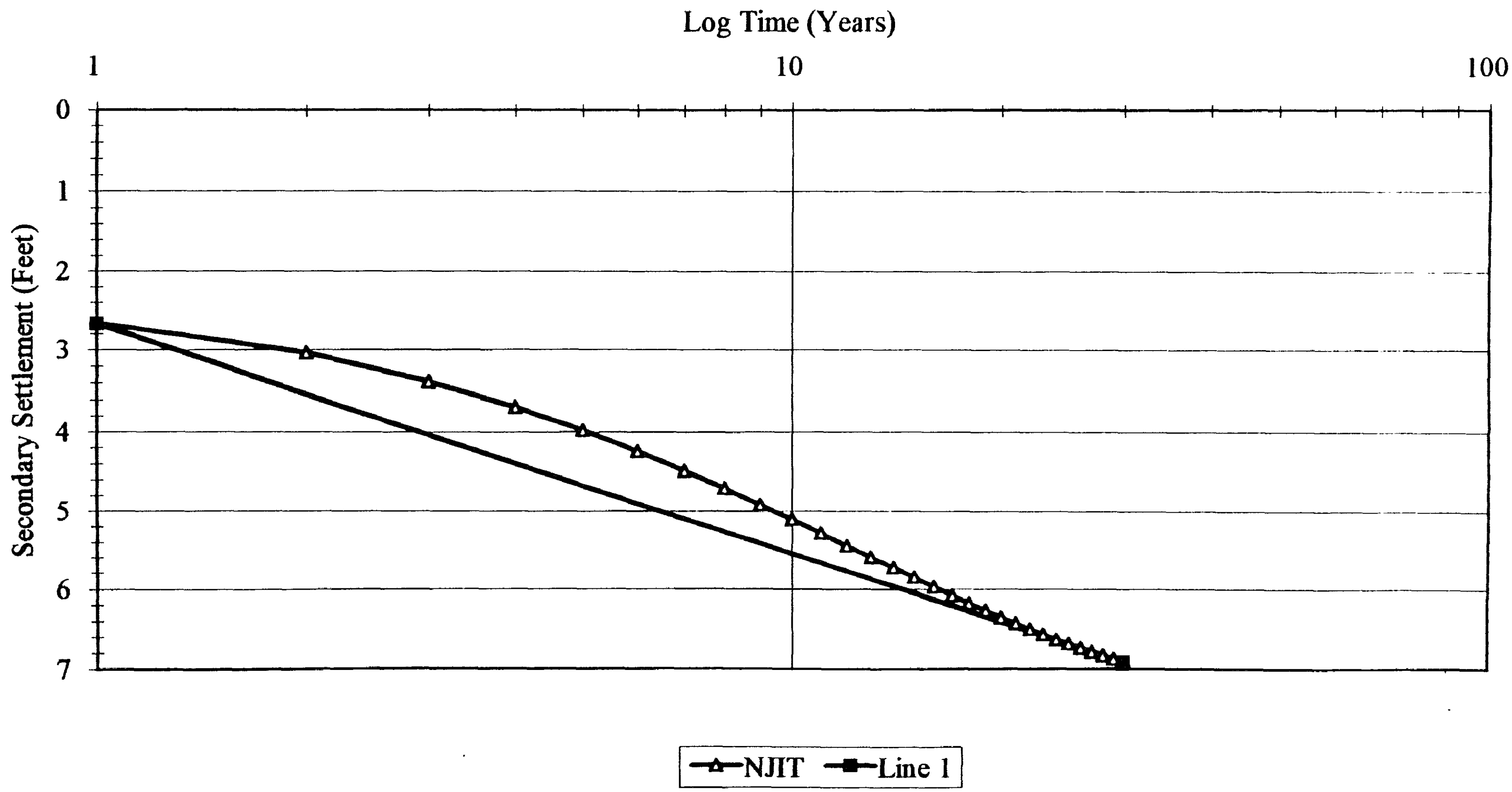

Figure 5.5 Linear Secondary Compression Ratio for the NJIT Model

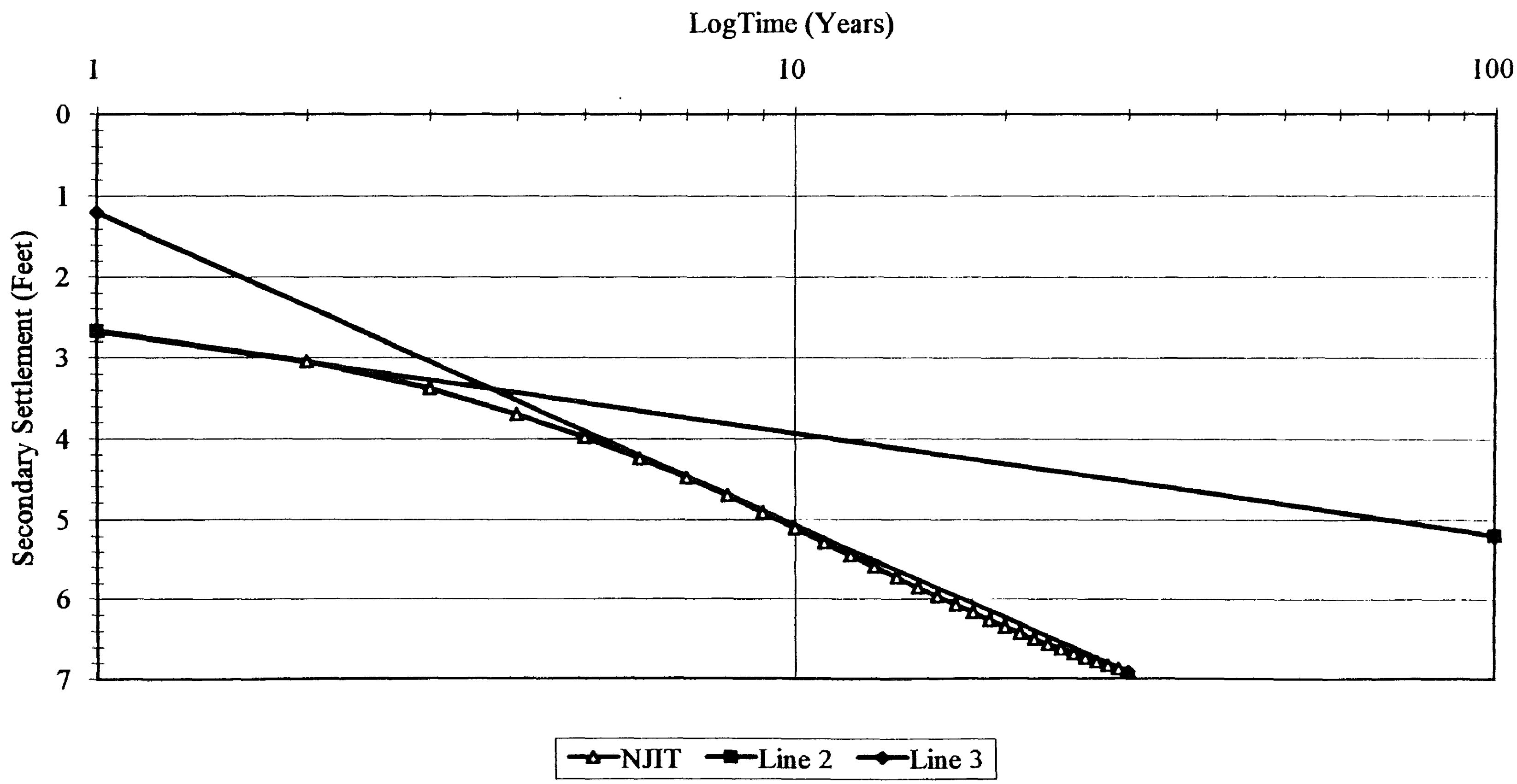

Figure 5.6 Two Phase Secondary Compression Ratio for the NJIT Model

CHAPTER 6

DISCUSSION OF RESULTS AND CONCLUSIONS

In order to validate the NJIT model, secondary settlements computed from the model will have to be correlated with field settlement measurements of landfills, but good field data is scarce. Some discussion on the relevance of field data for use in this study was presented in Chapter 2. Under these circumstances, it was decided to correlate the results of this study with those of Sowers, which is based on field data.

6.1 Discussion of Results

A comparison was made between the secondary settlement, and secondary compression ratio values of the Sowers, and NJIT model. This is shown in the secondary settlement vs time plot of Figure 6.1, and the secondary settlement vs log time plot of Figure 6.2. While the rates of settlement predicted by these the models appears to be similar, the calculated settlement values are higher for the NJIT model than for Sowers model. This can be attributed to a variety of reasons.

For the NJIT model, it is assumed that 100 percent of the gas generated by the landfill is collected by the gas venting system, this is not necessarily the case for Sowers model. It is the authors belief that one of the ways to increase settlement is to remove the gas generated due to biodegradation from the landfill. Venting of this gas allows the microorganisms to biodegrade more waste, thus allowing for an increase in settlement. This occurs since the gas now has a way to escape, instead of building up in the landfill, and slowing down the biodegradation process. Also, as more volume of gas is removed, the more volumetric strain, and vertical strain occurs. This causes more settlement.

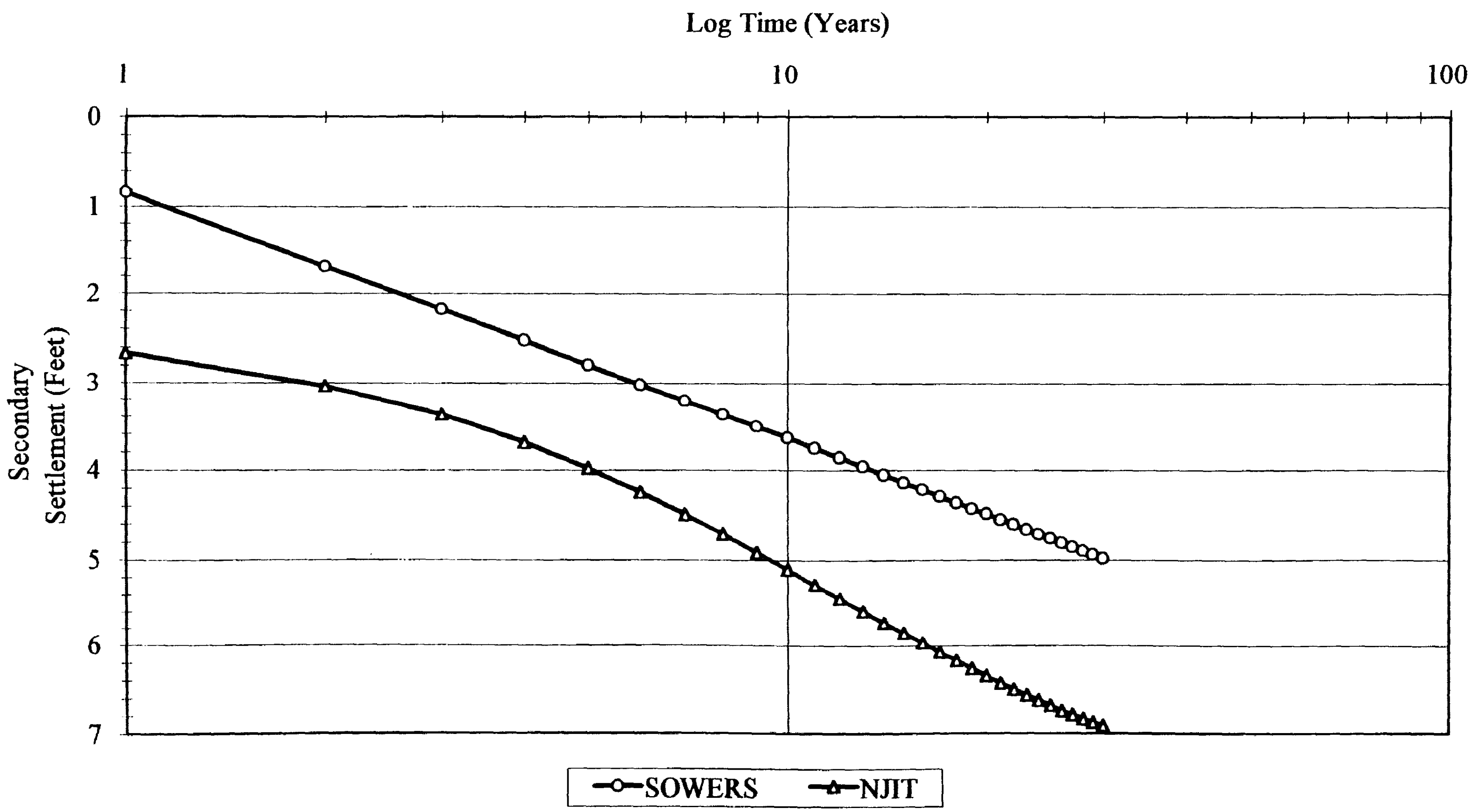

Figure 6.1 Comparison of Secondary Settlement vs Log Time Between the Models

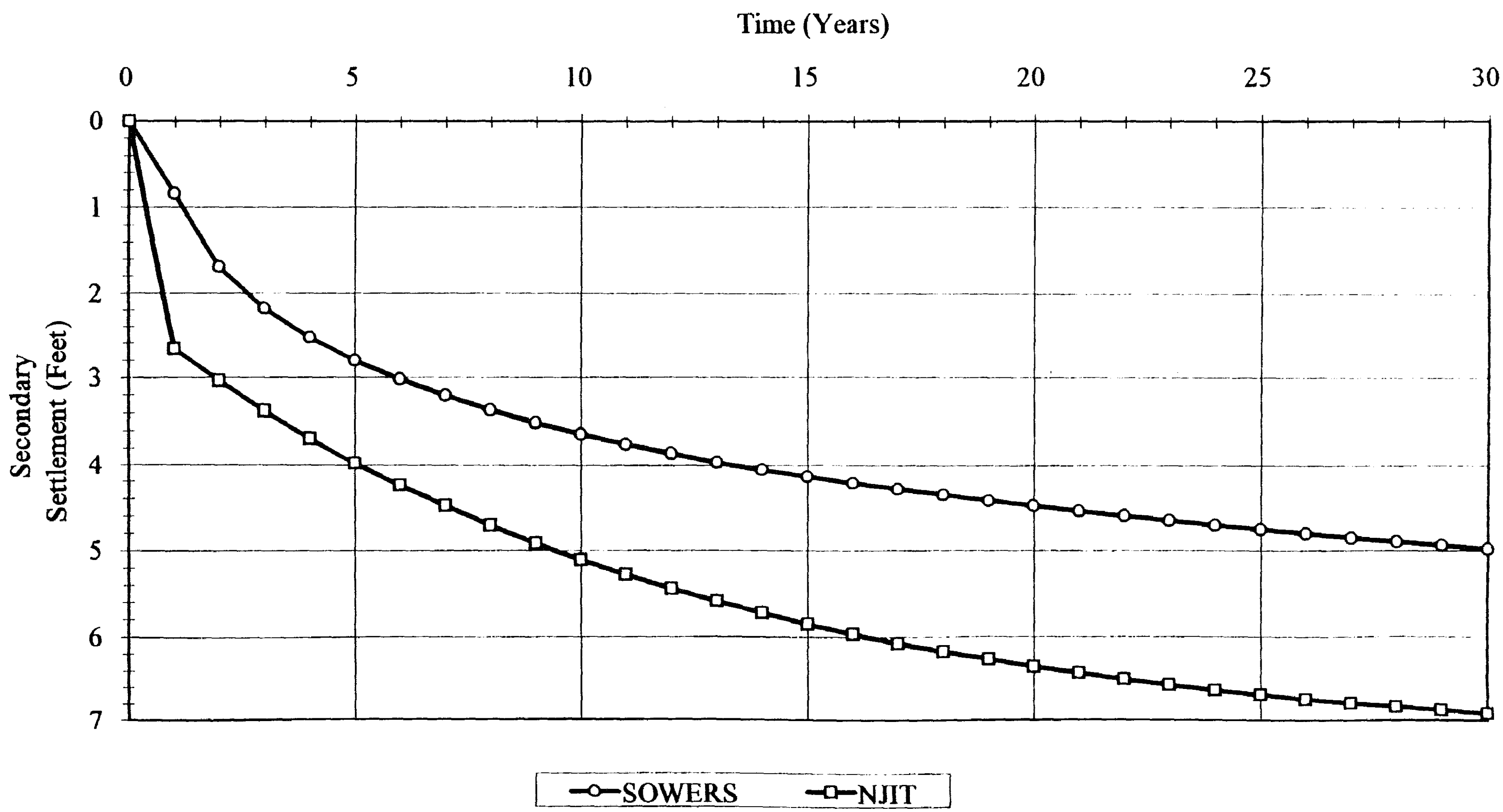

Figure 6.2 Comparison of Secondary Settlement vs Time Between the Models

Studies conducted by Sowers were on landfills probably constructed during the 1960's and early 1970's, just when landfill regulations were being drafted. This leads to the belief that the landfills studied by Sowers most likely had poorly designed, inadequate, or nonexistent gas venting systems. For such landfills, the rates of settlement will be lower than those occurring in landfills with adequate, and properly designed gas venting systems.

Landfill gas venting could also explain why the secondary compression ratio for the NJIT model is on the high side of the values presented by Sowers. As mentioned above, it is believed that gas venting will increase the settlement due to biodegradation in a landfill. This will then cause a corresponding increase in the secondary compression ratio. This explains the high value of "$c_{\alpha\varepsilon}$".

Another explanation for the higher secondary compression ratio, and settlement values for the NJIT model compared to Sowers model is the organic content of the waste. The predicted waste sample used for the NJIT model has a high organic content (almost 80 percent by weight). This may not have been the case for the waste disposed in the landfills studied by Sowers. The higher organic content would yield higher gas production, settlement values, and higher secondary compression ratios since there is more waste for the microorganisms to biodegrade. Holtz and Kovacs (1981) presents information on the secondary compression ratio of various soils. For amorphous and fibrous peat, a highly organic soil with almost 100 percent organic content, the range of the secondary compression ratio values are between 0.02 to 0.13, with the values of the secondary compression ratio for the assumed waste in this range.

In the future as more recycling is practiced, landfills will contain significant quantities of organic materials. This makes the NJIT model more revenant for estimating settlements.

As mentioned earlier, it is the contention of the author that the secondary compression ratio is not constant over the life of the landfill. It is believed that two values of "$c_{\alpha e}$" would better represent secondary settlement due to biodegradation than a single constant value of "$c_{\alpha e}$". More laboratory and field data is needed to verify this hypothesis.

6.2 Limitations of NJIT Model

There are some inherent limitations with the NJIT model. One limitation is the assumption made that volumetric strain is equal to vertical strain. While it can be valid for the center of the landfill, this assumption does not hold true for the perimeter of landfills. Also, the model assumes that the waste is continuous over the height of the landfill. It does not take into account the daily soil cover placed over the waste, materials used to cap the landfill, drainage layers, sequence of filling, and the heterogeneous composition of the waste, all which could alter the settlement, and gas production values.

6.3 Conclusions

Based on the results of this study, the following conclusions can be drawn:

1. It is possible to estimate secondary settlement due to biodegradation based on NJIT model utilizing gas generation curves.

2. The rate of secondary settlement can be accelerated by gas venting.

3. Rheological models based on secondary compression are not useful for estimating biodegradation settlements.

4. Models based on gas generation processes represent biodegradation more realistically than any other types of models.

6.4 Suggestions for Future Research

The following suggestions are being offered for future studies relating to biodegradation settlements of landfills.

1. Good field data regarding time settlement of landfills needs to be obtained.

2. Laboratory studies on actual waste samples simulating the processes involving biodegradation in landfills over a long period of time, need to be conducted. From these studies, data regarding the various phases of gas generation and parameters pertaining to gas generation curves needs to be obtained.

APPENDIX A
DETAILS OF DERIVATION OF THE NJIT MODEL AND SETTLEMENT CALCULATIONS USING OTHER MODELS

DETAILS OF DERIVATION OF THE NJIT MODEL AND SETTLEMENT CALCULATIONS USING OTHER MODELS

A.1 Derivation of NJIT Equation

$$V' = at \qquad (0 \leq t \geq T) \tag{4.1}$$

$$V' = aT\, e^{-b(t-T)} \qquad (t \geq T) \tag{4.2}$$

Integrating Equation 4.1 yields A.1 below.

$$V' = \int a\, t\, dt = aT^2 \tag{A.1}$$

Integrating Equation 4.2 yields A.2 below.

$$V' = \int aT\, e^{-b(T-t)}\, dt = aT/b\, (1 - e^{-b(t-T)}) \tag{A.2}$$

The summation of Equation A.1 and A.2 gives Equation 4.3 below.

$$V = (aT^2 / 2) + aT / b\, (1 - e^{-b(t-T)}) \tag{4.3}$$

A.2 Yen and Scanlon Model

Utilizing Equation 2.3 with $t_c = 120$ months and $t_e = 480$ months, the settlement is computed as shown .

$$t_m = 480 - (120 / 2) \tag{A.3}$$

This equation yields " t_m" equal to 420 months.

$$M = 0.088 - 0.038 \log (420) \tag{A.4}$$

Equation A.4 computes "M" to equal - 0.011 ft/month.

If the settlement is set equal to zero, the time it will take for this to occur can be found as shown below.

$$0 = 0.088 - 0.038 \log (t_m) \tag{A.5}$$

The answer for "t_m" is equal to 206.9 or approximately 207 months.

$$207 = t_e - (120 / 2) \quad \text{(A.6)}$$

This equation yields "t_e" equal to 267 months, or 22.25 years.

A.3 Gibson and Lo Model

To calculate settlement with this model, the following values are used for Equation 2.1. Using the low end of parameters for "b", the parameters are as follows, $b = 0.0006\ kPa^{-1}$, and with $\Delta\sigma = 100$ kPa, h = 40 ft, $\lambda/b = 0.001\ day^{-1}$, and t = 14600 days (40 years), secondary settlement can be calculated as follows.

$$S_S = 40 \times 100 \{0.0006 (1\text{-}\exp^{[-(0.001)\,14600]} \} \quad \text{(A.7)}$$

Secondary settlement is computed to equal to 2.4 feet.

Using the high end of the range of parameters with $b = 0.003\ kPa^{-1}$, secondary settlement is solved as shown.

$$S_S = 40 \times 100 \{0.003 (1\text{-}\exp^{[-(0.001)\,14600]} \} \quad \text{(A.8)}$$

For Equation A.8, "S_S" equals 12.0 feet.

A.4 Sowers Model

To calculate "$c_{\alpha e}$", Equation 5.1 is used to find the void ratio of the waste as shown by A.9 below.

$$32.68 = \{[2.0 + 0.2122 (2)]\ 62.4\} / (1 + e) \quad \text{(A.9)}$$

The void ratio is equal to 3.63.

Once the void ratio is known, Equation 2.5 can be used to find "$c_{\alpha\varepsilon}$".

$$c_{\alpha e} = 0.09 (3.63) / (1 + 3.63) \quad \text{(A.10)}$$

Equation A.10 yields "$c_{\alpha e}$" equal to 0.0705.

A sample calculation to find secondary settlement is shown below. The time used in this calculation was 10 years after landfill closure.

$$S_S = 40\ (0.07)\ \log\ (10/.5) \tag{A.11}$$

From Equation A.11, secondary settlement equals 3.64 feet. This corresponds to a fill height of 36.36 feet.

APPENDIX B
MASS BALANCE AND GAS GENERATION COMPUTATIONS

B.1 Mass Balance Calculations

Table B.1 Waste Characteristics

Component	Weight (lbs)	Percent By Weight	Uncompacted Unit Weight (lbs/ft^3)	W. C. Factor	W.C. Volume (ft^3)
Organic					
Food Waste	9	9	18	0.33	0.17
Paper	34	34	4	0.15	1.28
Cardboard	6	6	4	0.18	0.27
Plastic	7	7	4	0.1	0.18
Textiles	2	2	4	0.15	0.08
Rubber	0.5	0.5	9	0.3	0.02
Leather	0.5	0.5	9	0.3	0.02
Yard Waste	18.5	18.5	7	0.2	0.53
Wood	2	2	15	0.3	0.04
Total Organic		79.5			
Inorganic					
Glass	8	8	12	0.4	0.27
Tin Cans	6	6	12	0.15	0.08
Aluminum	0.5	0.5	12	0.15	0.01
Other Metal	3	3	12	0.3	0.08
Dirt, Ash Etc.	3	3	30	0.75	0.08
Total		100			3.06

Well Compacted unit weight = 32.68 lbs/ft^3

Table B.2 Chemical Breakdown of the Waste (By Percent)

Organic	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Food Waste	48.0	6.4	37.6	2.6	0.4	5.0
Paper	43.5	6.0	44.0	0.3	0.2	6.0
Cardboard	44.0	5.9	44.6	0.3	0.2	5.0
Plastic	60.0	7.2	22.8	-	-	10.0
Textiles	55.0	6.6	31.2	4.6	0.15	2.5
Rubber	78.0	10.0	-	2.0	-	10.0
Leather	60.0	8.0	11.6	10.0	0.4	10.0
Yard Waste	47.8	6.0	38.0	3.4	0.3	4.5
Wood	49.5	6.0	42.7	0.2	0.1	1.5
Inorganic						
Glass	0.5	0.1	0.4	-	-	98.9
Metals	4.5	0.6	4.3	-	-	90.5
Dirt, Ash Etc.	26.3	3.0	2.0	0.5	0.2	68.0

Table B.3 Dry Weight of the Organic Components

Component	Weight (lbs)	Moisture Content (Percent)	Dry Weight (lbs)
Food Waste	9	70	2.7
Paper	34	6	31.96
Cardboard	6	5	5.7
Plastic	7	2	6.86
Textiles	2	10	1.8
Rubber	0.5	2	0.49
Leather	0.5	10	0.45
Yard Waste	18.5	60	7.4
Wood	2	20	1.6

Table B.4 Organic Chemical Component Weights

Organic	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
Food Waste	1.30	0.17	1.02	0.07	0.01	0.14
Paper	13.90	1.92	14.06	0.10	0.06	1.92
Cardboard	2.51	0.34	2.54	0.02	0.01	0.29
Plastic	4.12	0.49	1.56	0.00	0.00	0.69
Textiles	0.99	0.12	0.56	0.08	0.00	0.05
Rubber	0.38	0.05	0.00	0.01	0.00	0.05
Leather	0.27	0.04	0.05	0.05	0.00	0.05
Yard Waste	3.54	0.44	2.81	0.25	0.02	0.33
Wood	0.79	0.10	0.68	0.00	0.00	0.02
Total (lbs)	27.79	3.66	23.29	0.58	0.11	3.52

Table B.5 The Mole Ratio for the Chemical Components

Component	Weight (lbs)	Atomic Weight	Number of Moles	Mole Ratio (N=1)
Carbon	27.79	12.01	2.31	56.33
Hydrogen	3.66	1.01	3.63	88.31
Oxygen	23.29	16.00	1.46	35.44
Nitrogen	0.58	14.01	0.04	1.00
Sulfur	0.11	32.07	0.00	0.09
Ash	3.52	-	-	-

CHEMICAL FORMULA

$$\mathbf{C_{56.33}H_{88.31}O_{35.44}N} \quad (4.4)$$

Table B.6 Dry Weight of the Waste for Decomposition

Component	Percent by Weight	Percent Moisture Content	Dry Weight (lbs)
Organic			
Food Waste	9	70	0.88
Paper	34	6	10.44
Cardboard	6	5	1.86
Plastic	7	2	2.24
Textiles	2	10	0.59
Rubber	0.5	2	0.16
Leather	0.5	10	0.15
Yard Waste	18.5	60	2.42
Wood	2	20	0.52
Inorganic			
Glass	8	2	2.56
Tin Cans	6	3	1.90
Aluminum	0.5	2	0.16
Other Metal	3	3	0.95
Dirt, Ash Etc.	3	8	0.90
Total Dry Weight			25.75

B.2 Gas Production Calculations

$$C_A H_B O_C N_D + [(4A\text{-}B\text{-}2C\text{-}3D)/4]\ H_2O \Rightarrow$$

$$[(4A\text{+}B\text{-}2C\text{-}3D)/8]\ CH_4 + [(4a\text{-}B\ \text{+}2C\ \text{+}3D)/8]\ CO_2 + NH_3 \qquad (4.5)$$

Where A = 56.33, B = 88.31, C = 35.44, and D = 1.

$$C_{56.33} H_{88.31}\ O_{35.44}\ N + 15.78\ H_2O + 29.97\ CH_4 + 26.36\ CO_2 + NH_3 \quad (B.1)$$

Table B.7 Formula Mass of Components

Molecular Formula	Formula Mass
$C_{56.33} H_{88.31} O_{35.44} N$	1345.31
15.78 H_2O	284
29.97 CH_4	479.52
26.36 CO_2	1159.84
NH_3	17

Recall, the dry weight of the waste equals 25.75 lbs. The dry weight of the waste that will be converted to gas is shown in Equation B.2

$$25.75 \times 0.197 = 5.07 \text{ lbs} \qquad \text{(B.2)}$$

The volume of Methane produced per cubic foot of waste can be calculated as follows.

$$(479.52 / 1345.31) \times 5.07 \text{ lbs} = 1.81 \text{ lbs Methane} \qquad \text{(B.3)}$$

To convert lbs of Methane, to cubic feet of Methane, the factor is 0.0448 lb/ ft^3

$$(1.81 \text{ lbs} / 0.0448 \text{ lb/ft}^3) = 40.4 \text{ ft}^3 \qquad \text{(B.4)}$$

The volume of Carbon Dioxide produced per cubic foot of waste is calculated as shown below.

$$(1159.84 / 1345.31) \times 5.07 \text{ lbs} = 4.37 \text{ lbs Carbon Dioxide} \qquad \text{(B.5)}$$

To convert to cubic feet of Carbon Dioxide, the factor is 0.1235 lb/ ft^3

$$4.37 \text{ lbs} / 0.1235 \text{ lb/ ft}^3 = 35.38 \text{ ft}^3 \qquad \text{(B.6)}$$

The total gas generated, along with the percent composition of the gas is calculated below.

$$40.4 \text{ ft}^3 + 35.38 \text{ ft}^3 = 75.78 \text{ ft}^3 \text{ gas} / \text{ft}^3 \text{ waste} \qquad \text{(B.7)}$$

$$\text{Methane} = (40.4 \text{ ft}^3 / 75.78 \text{ ft}^3) \times 100 = 53.31 \text{ percent} \qquad \text{(B.8)}$$

$$\text{Carbon Dioxide} = (35.38 \text{ f}^{t3} / 75.78 \text{ ft}^3) \times 100 = 46.69 \text{ percent} \qquad \text{(B.9)}$$

APPENDIX C
DETAILS OF THE NJIT MODEL

DETAILS OF THE NJIT MODEL

An explanation of the procedure involved in calculating settlement using the NJIT model is presented here through a sample calculation. Waste disposal was assumed to have occurred over a 10 year period, with the sample calculations illustrating settlement for year 2 (t = 12 years) after landfill closure. Settlement due to biodegradation was assumed to have occurred for a period of 30 years after landfill closure, the results of which are presented in Tables C.1 and C.2.

At first, "a", must be found. By setting Equation 4.3 equal to 0.95 the total volume of gas produced, the equation can be solved for "a" as shown below.

$$1/2(a)^2 + [a\,(10)\,/\,0.076753]\,(\,1 - e^{-\,0.076753\,(40-10)}\,) = 0.95\,(75.78) \qquad (C.1)$$

The value of "a" was found to be 0.43.

Once "a" is known, the volume of gas generated for the first 10 years of waste disposal can be calculated from Equation 4.1. This is " V' " of Table C.1.

$$V' = 0.43(10)^2 / 2 \qquad (C.2)$$

" V' " was found to equal 21.5 ft^3.

Then the volume of gas generated for the next 30 years can be calculated from Equation 4.2. This is " V' " of Table C.1.

$$V' = [(0.43 \times 10)/0.076753]\,(\,1 - e^{-\,0.076753\,(\,12-10\,)}\,) \qquad (C.3)$$

This calculation results in" V' "equal to 7.97 ft^3.

The summation of these values is then found to find the total gas production for that year. For year 12 the sum is 29.47 ft^3 . The summation of " V' " is represented by "V" in Table C.1.

The next step is to find the strain of the waste in the landfill. The sum of the total gas produced, is divided by the volume of the total gas generated, as calculated in appendix B. This is then multiplied by 0.197, corresponding to 19.7 percent gas generation, to yield the strain for the year in question. These values are represented by "ε" of Table C.2. For the calculations shown, the total volume of gas produced was 75.78 ft^3 of gas per cubic foot of waste.

$$\varepsilon = (29.47/75.78)\ (0.197) \tag{C.4}$$

The strain was found to equal 0.0766.

The change in strain between the present year, and the previous year is then computed. The strain for year x is subtracted from the strain for year x-1 and is represented by "Δε" of Table C.2. For the calculations shown, the strain for year 11 is equal to 0.0667.

$$0.0766 - 0.0667 = 0.010 \tag{C.5}$$

From this, the settlement due to biodegradation can be calculated. Except for year 1 after closure, the settlement is found in the following manner. The settlement for the year in question is found by adding the settlement from the previous year, to the product of the change in strain and the fill height for the previous year. This value is tabulated under "Settlement due to Biodegradation" of Table C.1. For the following calculations, the settlement for year 11 was 2.67 feet, corresponding to a fill height of 37.33 feet.

$$S_S = 2.67 + 37.33\ (0.010) \tag{C.6}$$

The settlement due to biodegradation for year 12 is 3.04 feet.

For year 1 after the landfill is closed, settlement due to biodegradation is found by multiplying the strain for year 1 by the fill height at closure.

$$40\,(0.067) = 2.68 \text{ feet} \qquad \text{(C.7)}$$

Finally, the fill height at a particular year can be calculated by subtracting the settlement value for that year from the fill height at closure. This is tabulated under "Fill Height" of Table C.1. For year 12, the fill height is found as shown.

$$40 - 3.04 = 36.96 \text{ feet} \qquad \text{(C.8)}$$

Table C.1 Results for the NJIT Model

Time (years)	Time after Closure (years)	V'	V'	V	Settlement due to Biodegradation (ft.)	Fill Height (ft.)
0		0	0.00	0.00		
1		0.22	0.00	0.22		
2		0.86	0.00	0.86		
3		1.94	0.00	1.94		
4		3.44	0.00	3.44		
5		5.38	0.00	5.38		
6		7.74	0.00	7.74		
7		10.54	0.00	10.54		
8		13.76	0.00	13.76		
9		17.42	0.00	17.42		
10	0	21.50	0.00	21.50	0.00	40.00
11	1	21.50	4.14	25.64	2.67	37.33
12	2	21.50	7.97	29.47	3.04	36.96
13	3	21.50	11.52	33.02	3.38	36.62
14	4	21.50	14.81	36.31	3.69	36.31
15	5	21.50	17.86	39.36	3.98	36.02
16	6	21.50	20.68	42.18	4.24	35.76
17	7	21.50	23.29	44.79	4.49	35.51
18	8	21.50	25.71	47.21	4.71	35.29
19	9	21.50	27.95	49.45	4.92	35.08
20	10	21.50	30.03	51.53	5.10	34.90
21	11	21.50	31.95	53.45	5.28	34.72
22	12	21.50	33.73	55.23	5.44	34.56
23	13	21.50	35.38	56.88	5.59	34.41
24	14	21.50	36.90	58.40	5.72	34.28
25	15	21.50	38.32	59.82	5.85	34.15
26	16	21.50	39.63	61.13	5.97	34.03
27	17	21.50	40.84	62.34	6.07	33.93
28	18	21.50	41.96	63.46	6.17	33.83
29	19	21.50	43.00	64.50	6.26	33.74
30	20	21.50	43.97	65.47	6.35	33.65
31	21	21.50	44.86	66.36	6.43	33.57
32	22	21.50	45.69	67.19	6.50	33.50
33	23	21.50	46.45	67.95	6.57	33.43
34	24	21.50	47.16	68.66	6.63	33.37
35	25	21.50	47.82	69.32	6.68	33.32
36	26	21.50	48.43	69.93	6.74	33.26
37	27	21.50	48.99	70.49	6.79	33.21
38	28	21.50	49.51	71.01	6.83	33.17
39	29	21.50	49.99	71.49	6.87	33.13
40	30	21.50	50.44	71.94	6.91	33.09

Table C.2 Results of Strain for the NJIT Model

Year	Year After Closure	ε	Δε
0		0.0000	
1		0.0006	
2		0.0022	
3		0.0050	
4		0.0089	
5		0.0140	
6		0.0201	
7		0.0274	
8		0.0358	
9		0.0453	
10	0	0.0559	
11	1	0.0667	
			0.0100
12	2	0.0766	
			0.0092
13	3	0.0858	
			0.0085
14	4	0.0944	
			0.0079
15	5	0.1023	
			0.0073
16	6	0.1096	
			0.0068
17	7	0.1164	
			0.0063
18	8	0.1227	
			0.0058
19	9	0.1286	
			0.0054
20	10	0.1339	
			0.0050
21	11	0.1389	
			0.0046
22	12	0.1436	
			0.0043

Table C.2 (continued) Results of Strain for the NJIT Model

Year	Year After Closure	ε	Δε
23	13	0.1479	
			0.0040
24	14	0.1518	
			0.0037
25	15	0.1555	
			0.0030
26	16	0.1589	
			0.0032
27	17	0.1621	
			0.0029
28	18	0.1650	
			0.0027
29	19	0.1677	
			0.0025
30	20	0.1702	
			0.0023
31	21	0.1725	
			0.0021
32	22	0.1747	
			0.0020
33	23	0.1767	
			0.0018
34	24	0.1785	
			0.0017
35	25	0.1802	
			0.0016
36	26	0.1818	
			0.0015
37	27	0.1832	
			0.0014
38	28	0.1846	
			0.0013
39	29	0.1859	
			0.0012
40	30	0.1870	

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