VOLUME 9

Deliverables to meet work plan objective 8: Further define and quantify the true costs and benefits of landfill bioreactors

9.1 Work Plan Objective and Deliverables

Objective 8 of the project work plan was:

> *Further define and quantify the true costs and benefits of landfill bioreactors*

The work plan identified the following methodology to meet objective 8:

> *A major goal of the project will be to quantify the actual costs of bioreactor landfill operation, both aerobic and anaerobic. The costs needed to operate a bioreactor will be determined. The benefits will be quantified to the extent possible. Benefits include increased landfill settlement and the resulting gain in landfill capacity. Other benefit issues to be addressed will include the landfill siting minimization and the possibility of a reduction in post-closure care.*

The deliverables identified in the work plan included:

- *Methodology for preparation of a cost/benefit analysis*
- *Periodic cost/benefit projection reports throughout project*
- *Final Report to include a Cost/Benefit Chapter describing potential impact of bioreactor landfill on post-closure care costs and financial responsibility regulations.*

9.2 Introduction

A new and emerging trend in waste management in the United States is to operate a landfill as a bioreactor. Bioreactor landfills differ from conventional landfills in that they are operated in a controlled fashion to create an in-situ waste environment more conducive to degradation by injecting moisture and/or air to the landfill. Much work, at both the laboratory- and field-scales, has been conducted documenting the many advantages associated with operating the landfill as a bioreactor (e.g., Pohland, 1995; Reinhart 1996; Reinhart and Townsend, 1998). Because effective operation of bioreactor landfills involves careful operation and construction of infrastructure beyond that necessary in traditional landfills, upfront capital and operating costs of bioreactor landfills are larger than those for traditional landfills. However, these costs may be off-set by economic advantages resulting from bioreactor landfill operation. Prior to investing in bioreactor landfills, landfill owners must be convinced that larger short-term expenses will be balanced by future economic benefits, including reduced long-term environmental risks which are difficult to financially quantify at present.

Operating a landfill as a bioreactor requires moisture addition to enhance waste degradation, both of which may extend the life of the landfill (i.e., active filling period), presenting financial benefits related to air space utilization (Hater, 2001). Economic benefits may also result from reduced leachate treatment/disposal costs, conserved landfill space, extended landfill life, deferred new cell and cap construction, earlier beneficial reuse of land, post-closure savings from fewer monitoring and financial assurance requirements, and more efficient gas collection with potential revenues from energy production (SAIC, 2000). These economic benefits may be diminished by costs associated with increased operating requirements to ensure that side seeps are controlled, odors are prevented, and health and safety are protected. Increased capital costs for liquid (and air in some cases) injection facilities and additional monitoring equipment to control bioreactor functions can also be expected. In some cases gas extraction equipment will be required earlier and beyond that required in the case of conventional landfilling.

To date, few studies have quantified the monetary benefits associated with bioreactor landfill operation or construction modes influence project economics. Economic studies of bioreactor landfills are frequently site-specific, focusing solely on communities considering this approach, thus few case studies are published in the literature. Gambelin et al (1998) concluded that a bioreactor landfill would cost $1.83/ton more than a dry tomb facility. Although the costs associated with the recirculation system were included in the analysis, the study lacked inclusion of any monetary gain associated with possible economic benefits such as airspace recovery and reduced leachate treatment. Chong et al (2005) conducted a cost-benefit analysis for semi-aerobic landfills (as-built systems) in Malaysia and found them to be economically comparable to conventional landfills. However, the analysis did not account for any monetary gains associated with recovered air space. Operation of the semi-aerobic landfill differs significantly from bioreactor operation (i.e., no air injection electricity costs) in the US, thus care should be taken when extrapolating results to bioreactor landfills. Hater et al. (2001) compared eight different scenarios of retrofit, hybrid, facultative, and conventional landfills. From their analysis they concluded that over the long term, increased landfill life associated with bioreactors permits longer use of existing landfills and therefore fewer new permits would be necessary. Yolo County Public Works Department (2000) conducted a comparison of anaerobic bioreactor and conventional landfills, while considering benefits associated with airspace recovery, reduced leachate treatment, and revenue associated with energy production from methane. The authors concluded that cost of a controlled bioreactor landfill with and without methane control was favorable when compared to a conventional landfill.

The economic case studies conducted to date provide a framework for economic analysis, but lack the details required to address important questions such as when it may be economically advantageous to construct a bioreactor landfill (i.e., are retrofit bioreactor landfills economically viable), if adding air is economically advantageous, and how different modes of operation (anaerobic, aerobic, and hybrid) influence economics. Conducting a detailed investigation of the costs and potential benefits associated with bioreactor landfills is necessary to address these questions.

The purpose of this paper is to describe an economic model developed to evaluate the impact of various operational (anaerobic, aerobic, or hybrid) and construction (retrofit and as-built) bioreactor landfill strategies on life-cycle cost. The specific objectives of this work were to (1) evaluate the costs and benefits associated with both as-built and retrofit bioreactor landfills and determine how they influence overall landfill economics, (2) compare bioreactor landfill economics to those of traditional (dry tomb) landfills, (3) determine how varying air addition times when operating hybrid bioreactor landfills influences total costs, and (4) evaluate the sensitivity of operational parameters (e.g., electricity costs) and/or anticipated benefits (e.g., amount of settlement) on bioreactor landfill economics.

9.3 Model Description

A spreadsheet-based model incorporating economic factors (costs and benefits) related to traditional and bioreactor landfill operation to evaluate the influence of different construction modes (retrofit and as-built landfills) and operational schemes (aerobic, anaerobic, and hybrid) on bioreactor landfill economics was developed. Table 9.1 presents the differences associated with the landfill scenarios modeled. The four base cases for traditional, as-built bioreactor, retrofit bioreactor, and aerobic bioreactor landfills are provided in the Attachment at the end of this Volume.

For the purposes of this study, a hypothetical landfill cell was designed (based on Duffy (2005), with minor modifications). The footprint of the landfill cell was assumed to be a 13.4-ha square. The bottom liner system consisted of a compacted clay liner, a 1.5-mm high density polyethylene (HDPE) geomembrane, a geocomposite drainage layer, and a drainage layer. Within the drainage layer, perforated HDPE leachate collection pipes were placed at 60-m parallel spacing. The final cell cap consisted of a compacted clay cap, a 1-mm HDPE layer, a soil protective layer overlain with vegetation, and a stormwater management system (i.e., swales, discharge channels, and culverts). A gas control and collection system was also constructed and consisted of HDPE collection wells, header pipes, and condensate drip legs. Infrastructure constructed for bioreactor operation included air and leachate injection equipment and monitoring instruments (i.e, temperature, moisture and settlement).

The active filling period was five years, during which solid waste was accepted at a constant rate of 500 tonnes per day. Bioreactor operation occurred for a period of 10 years. In the as-built bioreactor, bioreactor operation commenced immediately and continued to year 10 (see Figure 9.1), while in the retrofit systems, bioreactor operation commenced in year 6. The post closure care (PCC) period begins at the end of active filling (year 5) and continues for 30 years, as per the current USEPA regulations (see Figure 9.1).

Simulations to evaluate the economics associated with both traditional and bioreactor landfills were conducted. Because costs and benefits associated with bioreactor landfills differ depending on the construction mode and operational scheme, several bioreactor scenarios were evaluated. The differences associated with the scenarios modeled are provided in Table 9.1. All costs and benefits for each simulation were tabulated, projected (using appropriate interest and inflation rates), and finally converted to a present worth (PW) total landfill cost for comparison. Table 9.1 provides a summary of the costs and benefits associated with each scenario modeled. The following sections describe in greater detail how costs and benefits were modeled

Table 9.1. Comparison of Landfill Scenarios.

Landfill Type	Landfill Definition	Potential Monetary Benefits	Operation and Maintenance	Leachate Volume Reduction	Air Injection Costs	Methane Utilization for Electricity Generation	Closure and Post Closure Care	Air Space Recovery
Traditional	Operated with intent of entombing waste	Utilization of methane for electricity generation	Typical costs (Table 3)	None	None	Gas collection begins in year 6, after closure. Gas generation parameters: Lo = 100 m^3 CH$_4$/Mg K = 0.04/yr	Typical costs (Table 4)	None
Anaerobic Retrofit Bioreactor	Bioreactor operation commences following active filling (year 6)	Leachate treatment savings; utilization of methane for electricity; air space recovery	Typical costs.	Yes, but begins in year 6. Only leachate not recirculated requires treatment. The landfill reaches field capacity in year 9.	None	Gas collection begins in year 6, after closure. Gas generation parameters: Pre-Field Capacity: Lo = 100 m^3 CH$_4$/Mg K = 0.04/yr Post-Filed Capacity: Lo = 100 m^3 CH$_4$/Mg K = 0.15/yr	A temporary cap is installed at the end of the active filling period. The final cap is constructed at the end of year 15. Bioreactor O&M costs are incurred during the PCC period.	Yes. All space is regained at the end of the bioreactor period (year 15) and prior to installation of a final cap.
Anaerobic As-Built Bioreactor	Bioreactor operation commences during active filling.	Leachate treatment savings; utilization of methane for electricity; air space recovery	In addition to typical costs, leachate recirculation costs are incurred	Yes. Begins immediately.	None	Gas collection begins in year 1 (although the capture efficiency is low). Lo = 100 m^3 CH$_4$/Mg K = 0.15/yr	A temporary cap is installed at the end of the active filling period. The final cap is constructed at the end of year 10. Bioreactor O&M costs are incurred during the PCC period.	Yes. All space is regained in real-time. In addition, cost savings associated with the deferment of the next cell construction is realized.
Retrofit Hybrid Bioreactor	Bioreactor operation commences following active filling (year 6). Air injection occurs for periods ranging between 0.25 to 5 years	Leachate treatment savings; utilization of methane for electricity; air space recovery	In addition to typical costs, leachate recirculation and air injection costs are incurred	Yes, but begins in year 6. Only leachate not recirculated requires treatment. The landfill reaches field capacity in year 9. During air injection, 50% of the leachate produced is evaporated.	Yes. Electricity and O&M costs associated with air blowers and the injection system are incurred during PCC.	Gas collection begins subsequent to active filling and air injection. Gas generation parameters: Pre-Field Capacity: Lo = 100 m^3 CH$_4$/Mg K = 0.04/yr Post-Field Capacity: Lo = 100 m^3 CH$_4$/Mg K = 0.15/yr	A temporary cap is installed at the end of the active filling period. The final cap is constructed at the end of year 10. Bioreactor O&M costs are incurred during the PCC period.	Yes. All space is regained at the end of the bioreactor period (year 15) and prior to installation of a final cap.
As-Built Hybrid Bioreactor	Bioreactor operation commences during active filling. Air injection occurs for periods ranging between 0.25 to 5 years	Leachate treatment savings; utilization of methane for electricity; air space recovery	In addition to typical costs, leachate recirculation and air injection costs are incurred	Yes. Begins immediately. Only leachate not recirculated requires treatment. The landfill reaches field capacity in year 3. During air injection, 50% of the leachate produced is evaporated.	Yes. Electricity and O&M costs associated with air blowers and the injection system are incurred during PCC.	Gas collection begins in year 1 (although the capture efficiency is low), but subsequent to air injection. Pre-Field Capacity: Lo = 100 m^3 CH$_4$/Mg K = 0.04/yr Post-Field Capacity: Lo = 100 m^3 CH$_4$/Mg K = 0.15/yr	A temporary cap is installed at the end of the active filling period. The final cap is constructed at the end of year 10. Bioreactor O&M costs are incurred during the PCC period.	Yes. All space is regained in real-time. In addition, cost savings associated with the deferment of the next cell construction is realized.
Aerobic Bioreactor	Bioreactor operation commences during active filling. Air injection occurs immediately and continues during entire bioreactor period.	Leachate treatment savings; utilization of methane for electricity; air space recovery	In addition to typical costs, leachate recirculation and air injection costs are incurred	Yes. Begins immediately. Only leachate not recirculated requires treatment. The landfill reaches field capacity in year 3. During air injection, 50% of the leachate produced is evaporated.	Yes. Electricity and O&M costs associated with air blowers and the injection system are incurred during PCC.	No gas is collected for electricity generation.	A temporary cap is installed at the end of the active filling period. The final cap is constructed at the end of year 10. Bioreactor O&M costs are incurred during the PCC period.	Yes. All space is regained in real-time. In addition, cost savings associated with the deferment of the next cell construction is realized.

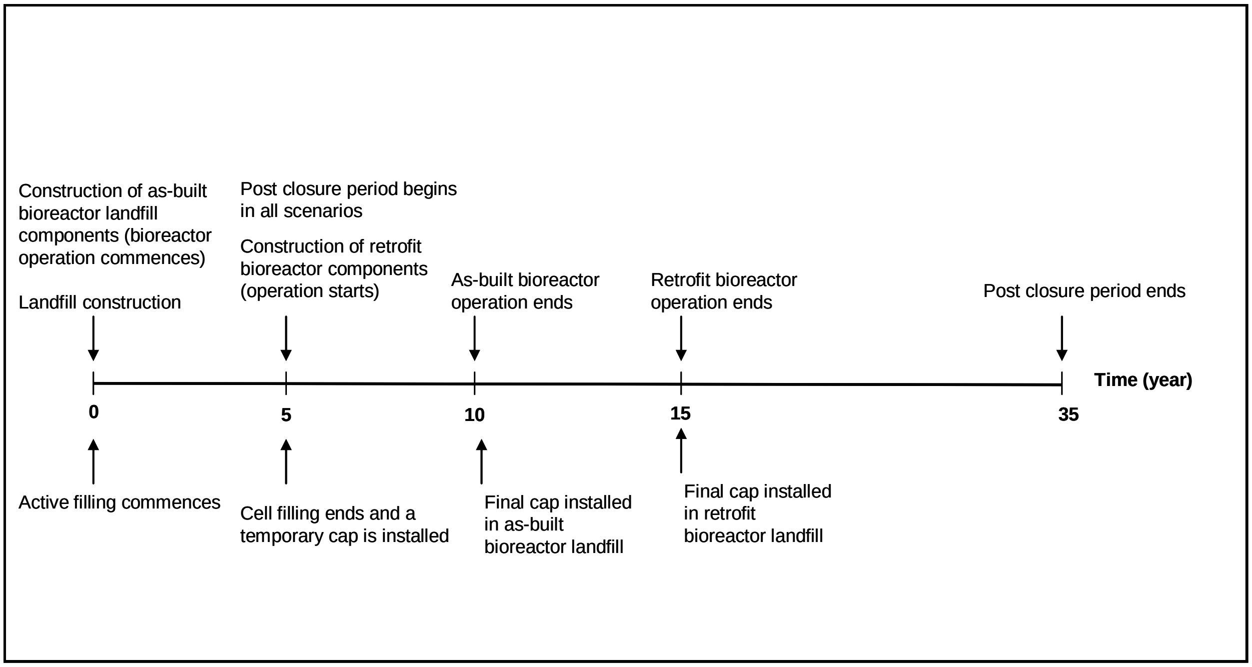


Figure 9.1. Timing of important activities in the life time of the study landfills

9.3.1 Construction and operation and monitoring costs

All costs generally associated with landfill construction were included. A detailed listing of construction costs is provided in Table 2 (Duffy, 2005a and 2005b). It was assumed that all construction costs were repaid during the active filling period (interest and inflation rates account for the time value of money) for all scenarios. In a traditional landfill, operation costs consisting of support staff, facility and equipment power costs, required environmental sampling, and engineering services were incurred during active filling. Maintenance costs were also included (i.e., gas collection and extraction). Subsequent to active filling, only maintenance costs remained; unlike construction costs, all operation and maintenance costs were realized as they occur.

In retrofit bioreactor landfills, construction costs were the same as traditional landfill costs (bioreactor operations commenced immediately following placement of a temporary cap). The costs associated with the infrastructure necessary for leachate recirculation and/or air injection systems (vertical wells) were realized at the time of temporary cap placement. Operation costs associated with a retrofit system include those incurred during operation of a traditional landfill, as well as electricity costs associated with liquid and/or air injection. Based on a user inputted liquid/air injection rate, recirculation/air injection system hydraulics, and the cost of electricity, an annual cost for injecting leachate and/or air was calculated. Leachate injection rates were based on 15-meter well spacing and injection rates of 8,640L/day-well (average value based on Jain et al., 2006). In addition to electricity, costs for inspecting and repairing potential leachate outbreaks along side slopes were included (Hater, 2001), as were costs associated with additional staff, sampling, and engineering services.

As-built bioreactor landfills differ from retrofit bioreactors in that leachate and/or air injection commences as waste is placed. Thus, all liquid and air injection infrastructure costs were added to the initial construction costs. Operation and maintenance costs for an as-built bioreactor landfill were similar to those of a retrofit bioreactor, except that electricity costs associated with liquid and/or air injection occurred during the active filling period.

Table 9.2. Landfill Design and Base Case Parameters and Conditions.

Parameter	***Value***
Waste Receipt/day	550 Mg
Volume	3.1×10^6 m^3
Density	650 kg/m^3
Waste:Soil	4:1
Area of the landfill	13.4 hectare
Tipping Fee	$40/waste ton
Inflation Rate	3%
Sinking Fund Interest Rate	4%
Interest Rate	5%
Total Settlement	20%
Leachate Recirculation Efficiency	75%
Year field Capacity is Attained	3
Number of injection wells/acre	16
Area of Landfill Aerated	25%
Oxygen Utilization Efficiency	75%
LandGEM Gas Degradation Rate During Bioreactor Operation	0.15/yr
LandGEM Gas Degradation Rate for Traditional Landfills	0.04/yr
Gas Capture Efficiency While Filling	35%
Waste Methane Potential	100 m^3 CH_4/Mg waste
Gas Capture Efficiency After Capping	90%
Electricity Price	$0.05/kW-hr
Gas use Efficiency	70%
Leachate Generation Rate Before Closure	9,350 L/ha-day
Post Closure Care Period Length	30 yrs
Air Flowrate	75% of maximum
Waste Biodegradable Fraction	0.45
On-Site Leachate Treatment	$0.024/L
Off-Site Leachate Treatment	$0.061/L

Table 9-3. Construction Costs.

Category	Item	Typical Cost
Initial Work	Survey of LF	$12,400 - $19,800/ha
	Clearing of LF Site	$2,500 - $7,400/ha
Bottom Liner System	Excavation	$247,000 - $741,000/ha
	Berm	$24,700 - $39,500/ha
	Clay layer	$79,000 - 400,000/ha
	Composite liner system	$259,000 - $371,000/ha
	QA/QC	$185,000 - $247,000/ha
*Leachate Collection System**	Leachate collection pipes Leachate sumps leachate storage tank/pond	$19,800 - $29,700/ha
*Air Injection System**	Blowers Piping and valves	$68,000/ha
Support Facilities	Offices and fencing	$1.17 - $1.77 million (based on size, small - large)
Gas Flare	1 flare/100 acres	$1000 - $1,200/ha
Engineering Costs	Design	1% of total cost

* These costs are only incurred during construction for as-built bioreactor landfills only. These costs are incurred during temporary cap installation for retrofit bioreactor landfills.

9.3.2 Closure and post-closure care period costs

In the traditional landfill, typical closure (final cover) and PCC costs were incorporated into the model (detailed costs are provided in Table 4). Although closure costs were incurred the year of closure (year five), funds were accumulated during active filling based on a sinking fund interest rate of 4% (interest rate is 5% and inflation rate is 3%), as were the PCC costs.

In the bioreactor scenarios, closure costs were incurred for both a temporary cap constructed at the end of year five and for a final cap installed after bioreactor landfill operation ceases (year 10 or 15). A temporary cap is necessary because of anticipated settlement resulting from bioreactor operation; allowing for additional waste placement at the end of the bioreactor period without destroying a more costly final cap. The air addition and/or liquid injection system (*i.e.,* piping and pumps) was installed at the time of temporary closure in the retrofit bioreactor.

Post closure in this work is defined as the period following the placement of the temporary cap to the end of the required monitoring period. The PCC period utilized in the base case simulations was 30 years, as dictated by RCRA Subtitle D. When operating a bioreactor, two distinct PCC periods occur. The first comprised the duration of bioreactor operation in which gas collection and leachate and/or air injection power and maintenance costs were incurred. These costs are discussed in more detail in the operation and maintenance section. The second period began the year bioreactor operation ends and continued until the end of the PCC period. Costs in this second PCC period were similar to those experienced during PCC periods of traditional landfills.

Table 9-4. Closure and Post-Closure Care Costs.

Category	Item	Typical Cost ($/ha)
Temporary Cap	Final Grades Survey	7,400 - 14,900
	Cover and Vegetative Soil	32,000 - 64,000
	Run-Off Control	12,400 - 17,300
	Gas Collection System *	61,800 – 74,100
	Leachate Recirculation System*	80,800
	Air Injection System*	68,000
Closure Costs	Final Grades Survey	7,400 - 14,800
	Compacted Clay Cap	64,200 - 126,000
	Geomembrane Cap	44,500 - 56,800
	Cover and Vegetative Soil	32,100 - 64,200
	Seed, mulch and fertilizer	2,500 - 4,900
	Run-Off Control	12,400 - 17,300
	QA/QC	185,000 - 247,000
*Post Closure Care Costs***	Security and Fencing	7 - 15/yr
	Final Cap and Cover	740 – 1,400/yr
	Landfill Gas Mechanics	1,100– 1,400/yr
	Wells/Probes	49 – 74/yr
	Environmental Monitoring	1,100 – 1,400/yr
	Gas Collection Maintenance	5% of capital costs/yr
	Leachate Mechanics	Treatment costs associated with leachate treatment

* in the as-built bioreactor, these costs are realized during landfill construction

** operation costs associated with leachate and/or air injection are incurred during the post-closure care period during bioreactor operation

9.3.3 Leachate treatment costs and savings

A typical leachate generation rate of 9,350 L/ha-day during active filling was assumed (Vesilind et al., 2002) for all scenarios. Post-capping leachate generation trends typically decline after capping, thus decreased rates based on a literature survey outlined by Rooker (2000) were incorporated into the model. Average unit treatment costs ($0.024/L and $0.061/L for on-site and off-site treatment), respectively, based on a literature review conducted by Berge (2006)) were utilized in the base case. Additional simulations were conducted to evaluate the influence of a range of unit leachate treatment costs. Leachate treatment costs were realized annually. In the traditional landfill, all leachate generated required treatment. In the bioreactor simulations, only leachate not recirculated required treatment.

Attaining adequate moisture is a critical component of bioreactor landfill operation. Optimal bioreactor operation occurs between moisture contents of 40 and 70%, by weight (Reinhart and Townsend, 1997). Benson et al. (2007) calculated that approximately 550 L of liquids/Mg of waste above that initially present are necessary for a landfill to reach field capacity (field capacity is defined as a moisture content of 45%, by weight). Moisture from recirculating leachate alone is generally not sufficient to reach field capacity conditions in a reasonable period of time. Thus, supplemental liquid addition is often necessary. In this study, it is assumed that supplemental liquids were added at rates that allow field capacity to be reached in three years. The volume of supplemental liquid addition depends on the mass of waste and volume of leachate recirculated. Although there can be potential costs (i.e., pumping of groundwater) or benefits (i.e., addition of wastewaters) associated with supplemental liquids, these implications are not incorporated in the economic calculations. According to field-scale studies conducted by Read et al. (2001), approximately 50% of leachate produced is lost due to evaporation in aerobic landfills because of increased in-situ temperatures (as high as 70°C). Thus, a greater volume of supplemental liquids may be necessary in aerobic or hybrid bioreactor landfills, however significant leachate volume loss due to evaporation can potentially lead to high treatment cost savings.

An advantage associated with bioreactor landfills is their capacity to treat leachate in-situ, with potential cost savings. It was assumed that leachate being recirculated did not require additional treatment. Thus, only leachate not recirculated required treatment (either on-site or off-site). Both Reinhart and Townsend (1998) and Benson et al. (2007) reported recirculation rates to vary from 40 to 100% of leachate produced. Simulations conducted in this study evaluated recirculation of 50, 75, and 100% of generated leachate.

9.3.4 Gas generation, collection, and utilization costs and benefits

Gas generation in all scenarios was calculated using the EPA LandGem equation:

$$Q_{CH_4} = \sum_{i=1}^{n} kL_o M_i e^{-kt_i} \qquad (1)$$

where, Q_{CH4} is the annual methane generation, i is one year time increment, n is the number of years since first waste placement, k is the methane generation rate, L_o is the potential methane generation capacity, M_i is the mass of waste accepted in the i^{th} year, and t_i is the age of the waste accepted.

Utilizing captured methane to generate electricity presents potential revenue associated with both traditional and bioreactor landfills. In traditional landfills, it was assumed that gas generated during active filling could not be used for electricity generation (collection efficiencies are low with an open landfill and thus do not justify gas engine purchase). A L_o value of 100 m^3 CH_4/Mg waste and a first-order degradation rate constant of 0.04/yr were used in the traditional landfill simulations because they are parameters that have been found to adequately describe gas generation in traditional landfills (USEPA, 1997). After filling, 90% (Spokas et al., 2006) of the gas generated was collected. It was assumed that all collected gas could be utilized with 100% efficiency. Gas, if utilized, fueled an internal combustion engine (most commonly used equipment; USEPA, 1996) to produce electricity. The engine was purchased during the year of closure (capital cost of \$1400/kW and operation and maintenance costs of \$0.0025/kW-yr; taken from USEPA, 1996, adjusted to present day costs) and were repaid over the entire gas extraction and utilization period (yrs 6 – 15). Associated operation and maintenance costs were encumbered over the same period. Engine capacity was determined by weighing engine capital and operating costs against potential income to ensure maximum profits were realized. Total profits were defined as the revenue from electricity generation minus the costs associated with the purchase and operation of the gas engine. A selling price of \$0.05/kwhr (Ladner, 2006) for the generated electricity was used in the base case simulation to determine associated revenue. Additional simulations were conducted to evaluate the influence of selling prices on total project cost.

Retrofit gas collection and subsequent use for electricity differed from traditional landfills. During filling, when the retrofit bioreactor landfill behaves similarly to a traditional landfill (i.e., no liquid or air injection), gas generation was calculated using the EPA LandGem equation with L_o (100 m^3 CH_4/Mg waste) and k (0.04/day) values typical of traditional landfills. Once the landfill is capped and bioreactor operation commences (i.e., leachate recirculation), gas generation rates increase (Faour et al., 2006). The k value was increased over a three-year period (time to reach field capacity) to 0.15/day (Faour et al., 2006) to account for increased methane generation. The monetary gain associated with gas production was based on an electricity price of 0.05/kWh (Ladner, 2006). Gas utilization equipment was purchased immediately following closure, just prior to use. Engine capacity was determined as described previously. Gas generation in an as-built bioreactor landfill was similar to that of a retrofit bioreactor. However, in as-built systems, bioreactor operation commenced immediately, thus the k value was modified accordingly. Field capacity was assumed to be attained in year three, by which time the k was 0.15/day. An assumed gas capture efficiency of 35% (Spokas et al., 2006) was used for the open cell.

When adding air, it was assumed that methane was not generated, thus there was no gas capture and use during aeration. Gas utilization equipment (if used) was purchased immediately prior to use (subsequent to air addition). During air addition, a portion of the biodegradable waste fraction degrades, influencing the future methane potential of the waste. Once air addition ends and anaerobic conditions are established, associated reductions become important. Reduced waste methane potentials were calculated based on air injection flow rates, oxygen utilization efficiencies (75% in the base case), and the stoichiometric air addition ratio (approximately 2.09×10^6 L air/Mg waste) necessary to completely remove the biodegradable waste fraction (biodegradable fraction assumed to be 0.45). Reductions were accumulated, subtracted from initial methane potential, and subsequently applied to the gas generation model in the year anaerobic conditions reestablished. It is important to note that the fraction of oxygen supplied that was used for degradation (oxygen utilization rate) has not yet been explored in either field- or laboratory-scale experiments, but is an integral part of evaluating project economics. Although a utilization efficiency of 75% was assumed in this study, model simulations evaluating the influence of efficiency were also conducted.

When utilizing captured methane for electricity generation, tax benefits may be obtained by landfill owners. However, uncertainty associated with the future of tax benefits precluded them from being considered in this model.

9.3.5 Air injection costs

Model structure allows for air injection to occur after the temporary capping of the landfill and bioreactor operation commenced. Air injection periods from 0.25 to five years were modeled. Air injection electricity costs were calculated based on user inputted flow rates, injection system hydraulics, a required output pressure of 13 kN/m^2

(Jain et al., 2005b), and the cost of electricity. In the hypothetical landfill scenarios modeled, air flow rates were assumed to be 75% of the maximum physically allowable flow rate, which was determined by assuming a typical air injection well spacing of 15 m (Jain et al., 2005a) and data provided by Jain et al. (2005b). It was also assumed that air was only injected into 25% of the landfill at any time.

9.3.6 Airspace recovery benefits

Airspace recovery is the amount of space regained as a result of the addition of liquid and/or air (does not exist in the traditional landfill). A recoverable volume of airspace can be calculated based on the amount of settlement, landfill volume, and a reutilization factor. Not all of the recovered volume can be reused, particularly if some of the recovered space was located on the side slopes. The reutilization factor takes this into account and was defined as the fraction of the recovered volume that can generate revenue by additional waste placement. Equation 2 describes the monetary gain associated with recovering airspace.

$$AR = SV_{LF}UDRT \tag{2}$$

where, AR is the monetary benefit associated with the recovered air space ($/yr), S is the annual settlement fraction achieved (yr^{-1}), V_{LF} is the landfill total volume (m^3), D is the waste density (assumed to be 650 kg/m^3), U is the reutilization factor, R accounts for the additional volume of soil, and T is the tipping fee ($/kg).

Although actual air space gain occurs incrementally as waste degrades throughout bioreactor operation, in retrofit bioreactors the space is not reutilized until the end of the bioreactor period. A reutilization factor of 0.7 was used for retrofit bioreactor landfills.

Unlike the retrofit bioreactor landfill, the monetary gain achieved as a result of yearly airspace recovery was realized in real time in as-built bioreactors because additional waste could be placed as the space was regained. When operating as an as-built bioreactor, an additional monetary benefit was calculated as a result of delaying liner construction of a new landfill cell. This amount was calculated by determining the number of additional days of waste placement in the current cell (based on waste receipt rates and mass of waste) and taking into account the cost of the bottom liner and the time value of money (interest rate of 5% and inflation rate of 3%).

9.4 Model Inputs

Base cases for each landfill type were simulated; conditions are provided in Table 2. Subsequently, sensitivity analyses were conducted by varying landfill parameters to explore their impact on cost. Sensitivity analyses were also conducted on variables in which little field-scale information exists to generate data for input parameters. Values utilized in the sensitivity analysis are provided in Table 5.

Table 9-5. Conditions Evaluated in Sensitivity Analyses.

Parameter	***Values Evaluated***
Total Settlement	10, 20 and 30%
Post Closure Care Period Length	10, 20 and 30 yrs
Air Addition Duration	0.25, 1, 2, 3, 4 and 5 yrs
Leachate Recirculation Efficiency	50, 75, and 100%
On-Site Leachate Treatment Costs	\$0.001, \$0.024 and \$0.048/L
Off-Site Leachate Treatment Costs	\$0.016, \$0.061 and \$0.106/L
Oxygen Utilization Efficiency	50, 75 and 100%
Gas Selling Price	\$0.03, \$0.05, and \$0.1/kW-hr
Area of Landfill Aerated	25, 50, 75 and 100%

9.5 Discussion of Results

Figure 9.2 provides a comparison of retrofit bioreactor, as-built bioreactor, and aerobic bioreactor landfill PW costs to traditional PW costs for base case scenarios. The retrofit bioreactor landfill was approximately 8% more expensive than the traditional landfill, while both the as-built and aerobic bioreactor landfills were 20% and 13% less costly than the traditional landfill. These differences are largely due to the value of airspace recovered, recovery and subsequent use of captured methane, and, in the as-built and aerobic bioreactor landfills, the significant reduction in leachate volume requiring treatment during active landfilling.

The distribution of costs and benefits associated with the base case simulations for each landfill type is provided in Figure 9.3. Construction costs represent the majority of PW costs for all landfill types, ranging from 43 to 57% of the total cost. Because as-built bioreactor landfills (aerobic bioreactor simulated is also as-built) require moisture and/or air addition infrastructure at commencement of landfill operation, their associated construction costs are larger. The largest benefit associated with the bioreactor landfills is revenue gained from airspace recovery, while the component providing the most savings is leachate treatment. These two benefits, airspace recovery and a reduction in leachate treatment costs, are the primary reason the as-built anaerobic and aerobic bioreactor landfills are less costly than the traditional landfill. Retrofit bioreactor landfills do not have the same airspace benefits and leachate treatment savings associated with the as-built and aerobic bioreactors because the benefits are realized after the time of greatest impact.

Interesting to note are the costs associated with PCC. PCC costs associated with each bioreactor are greater than the PCC costs incurred when operating a traditional landfill. This is primarily because of the additional costs associated with bioreactor operation and monitoring incurred subsequent to closure that are included in PCC costs.

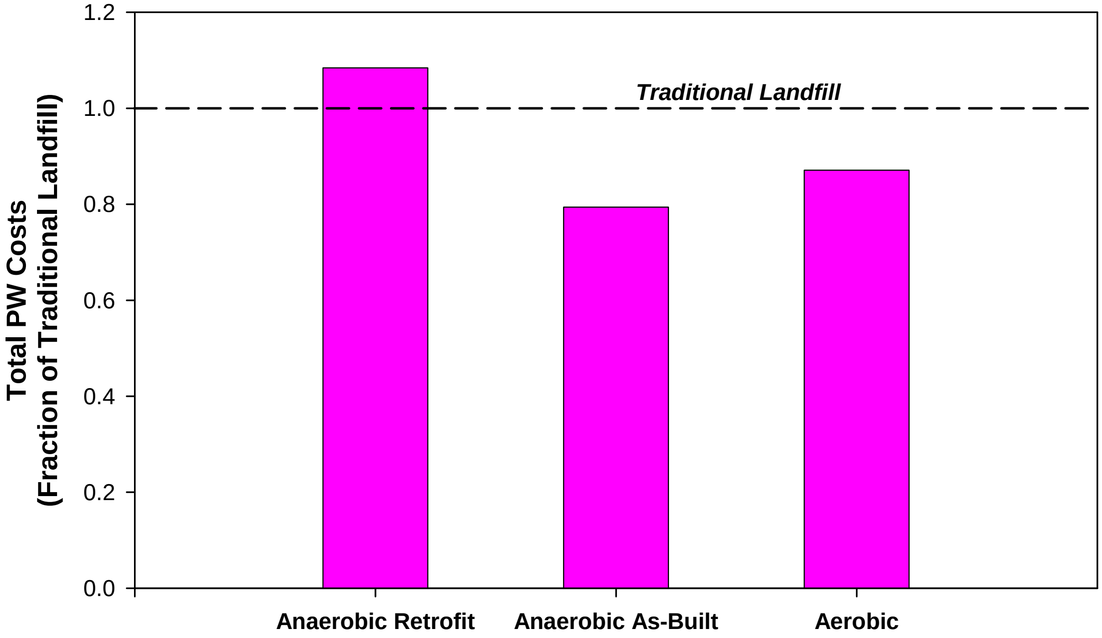


Figure 9.2. A comparison of bioreactor and traditional landfill PW costs.

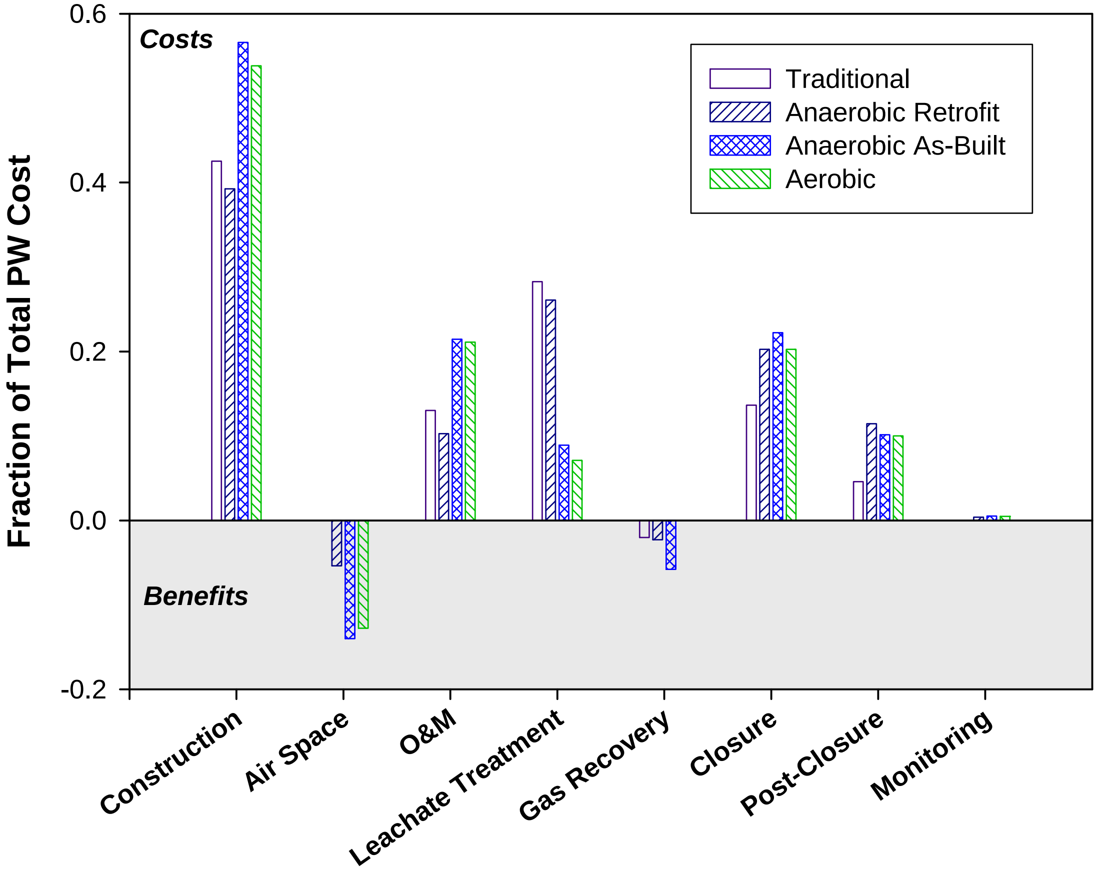


Figure 9.3. Distribution and comparison of bioreactor and traditional landfill PW costs.

9.5.1 Influence of aeration duration on bioreactor landfill economics

Aeration duration (ranging from 0.25 to five years) appears to have a very slight impact on total PW, as illustrated in Figure 9.4. The PW costs increase by less than 2% for both the as-built and retrofit systems after aerating for 5 years. The influence of aeration duration on distribution of costs for both retrofit and as-built hybrid bioreactor landfills is presented in Figure 9.5. Construction costs continue to dominate landfill economics.

Factors hypothesized to influence changes in total cost of hybrid bioreactor landfills include operation and monitoring (i.e., air addition and leachate recirculation), gas recovery and use costs and benefits, and leachate treatment savings. When examining the distributions provided in Figure 9.5, there is surprisingly little change in distributions as aeration duration increases. The item that exhibited the most substantial change (2 to 3% decline) for both the as-built and retrofit hybrid bioreactor landfills is the benefit associated with gas recovery and subsequent use for electricity generation. Operation and monitoring costs did not increase significantly with increases in aeration duration, as illustrated with similar trends in the both the operation and monitoring and PCC costs (Figure 9.5).

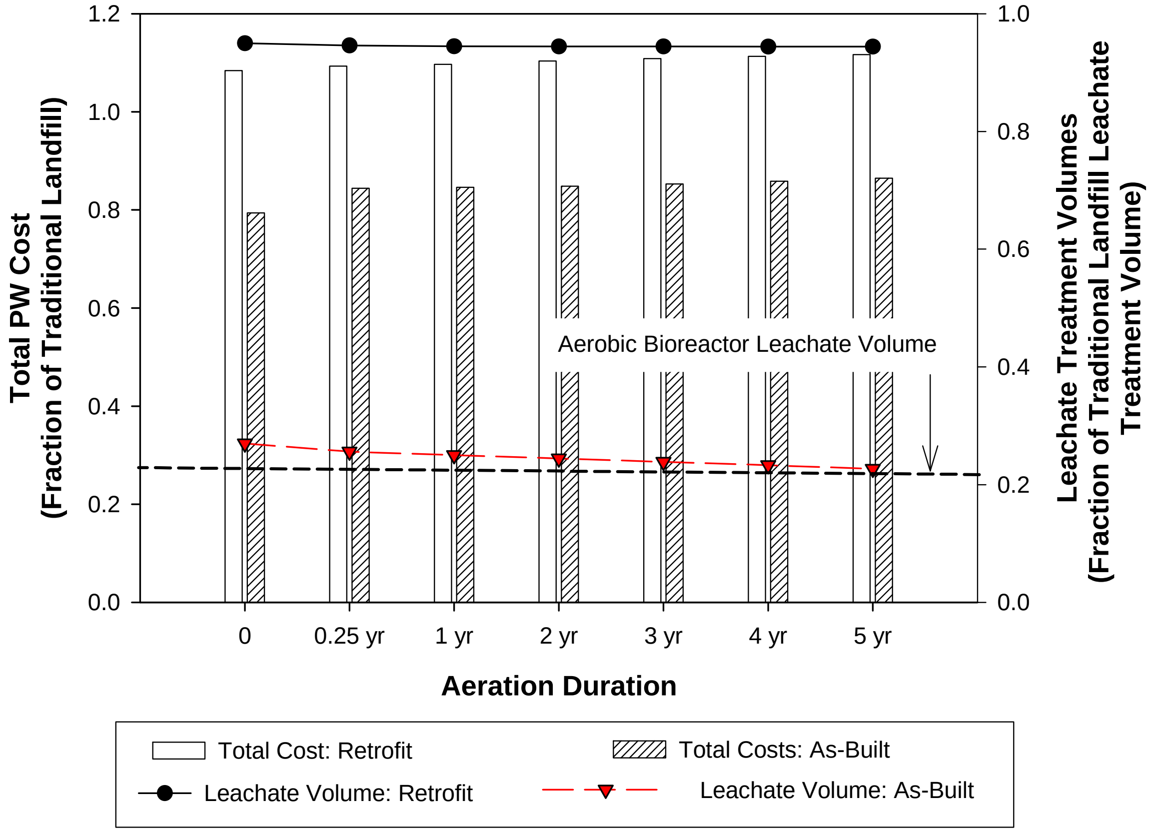
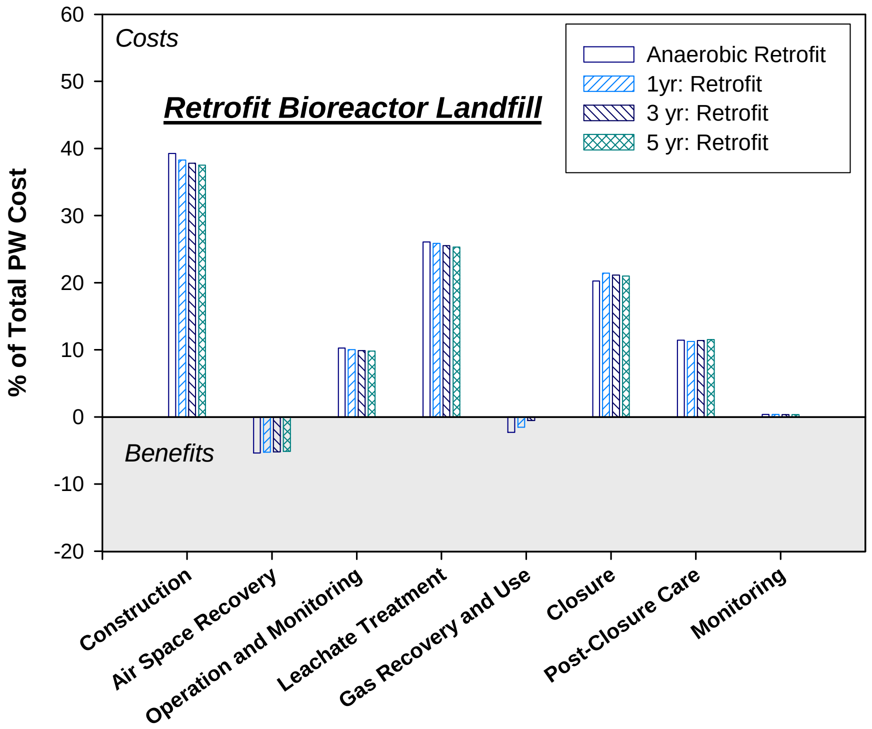
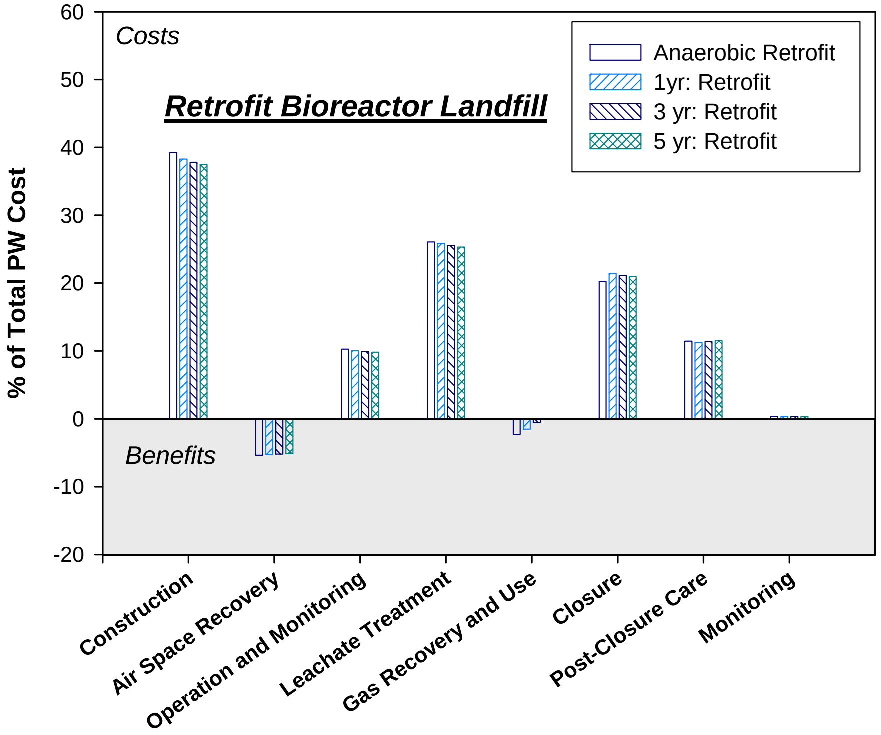


Figure 9.4. Total PW costs associated with hybrid bioreactor landfills as a fraction of traditional landfills and the influence of aeration duration on leachate volume requiring treatment for base case simulations.



(a)



(b)

Figure 9.5. Influence of aeration duration on distribution of PW costs for: (a) retrofit hybrid bioreactor landfill and (b) as-built hybrid bioreactor landfills.

9.5.2 Leachate treatment

Trends illustrating differences with volumes of leachate treated in hybrid and aerobic bioreactors and traditional landfills are included in Figure 9.4. Operating an as-built bioreactor landfill results in considerable leachate volume reductions when compared to traditional landfills, while the impact is relatively minor when operating retrofit systems. Leachate treatment costs for aerobic landfills are lower than those associated with traditional landfills and anaerobic bioreactor landfills. Lower savings are realized in retrofit bioreactors because the majority of leachate is produced prior to commencement of bioreactor operations and thus requires treatment. Aerobic bioreactor landfills (aeration for entire bioreactor period) results in the lowest leachate volumes requiring treatment because of the loss of leachate via evaporation. It is also interesting to note that as aeration duration increases, changes in leachate treatment costs are negligible for retrofit systems, while more significant treatment savings are realized for as-built bioreactors.

Factors that may influence total landfill leachate treatment costs include leachate recirculation efficiency and unit treatment costs. Figures 9.6 and 9.7 illustrate how treatment costs are influenced by the percentage of leachate recirculated (Figure 9.6) and unit volumetric treatment costs (Figure 9.7). The volume of leachate requiring treatment (and thus treatment costs) decrease significantly as the percentage of leachate recirculated increases in as-built hybrid systems, while negligible change is observed in the retrofit system (for reasons discussed previously). Accordingly, increasing recirculation percentage has a significant influence on as-built bioreactor landfill total landfill PW cost, as illustrated in Figure 9.6. As the recirculation efficiency increases from 50 to 100%, the total PW cost decreases by approximately 14% in as-built systems. When examining the influence of unit leachate treatment costs (Figure 9.7), it is interesting to note the significant treatment savings associated with as-built bioreactors may only occur when the unit treatment costs exceed 0.02 $/L. Additionally, as the unit cost for leachate treatment increases, the differential between as-built and retrofit bioreactor landfills also increases substantially.

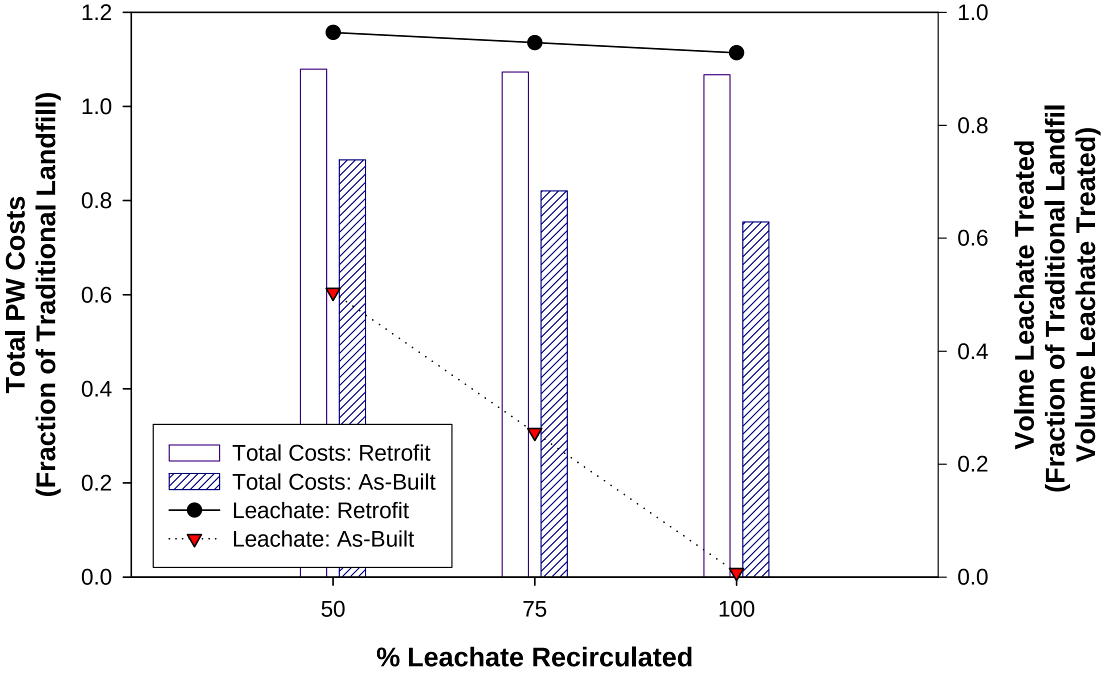


Figure 9.6. The influence of leachate recirculation percentages and leachate treatment volumes on total PW costs for retrofit and as-built bioreactor landfills.

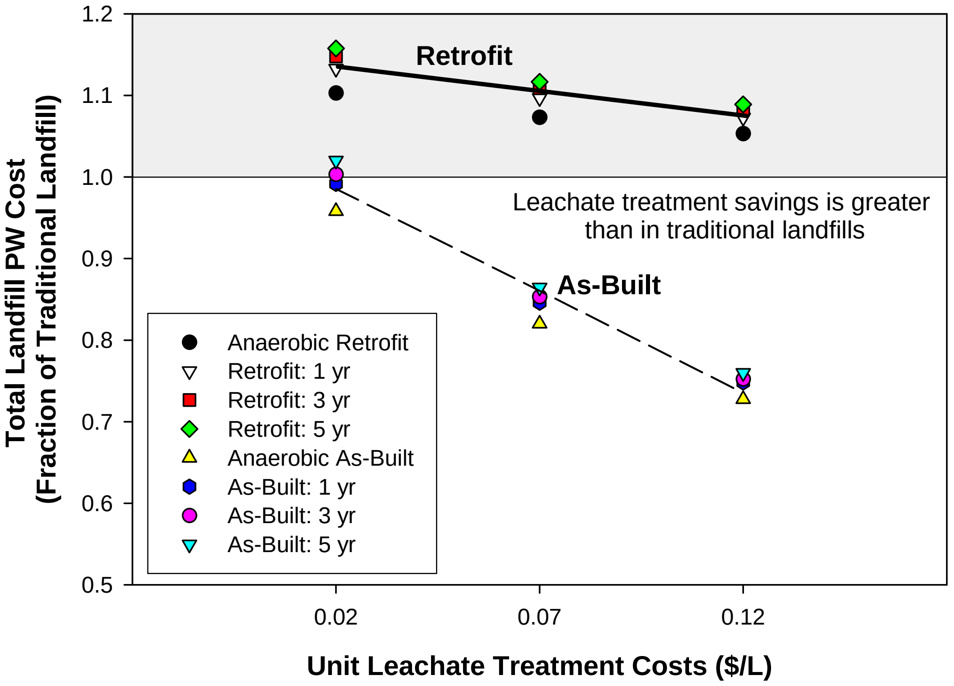


Figure 9.7. Comparison of bioreactor and traditional landfill PW leachate treatment costs as a function of unit leachate treatment costs.

9.5.3 Gas recovery for subsequent use

As shown in Figure 9.8, simulation results indicate that collecting gas for electricity generation is less economically attractive for retrofit hybrids at all aeration durations than traditional landfills. Because aeration leads to waste degradation via a metabolic route that does not produce methane, the monetary benefit associated with utilization of methane for electricity decreases as aeration duration increases. In as-built hybrid systems, recovering gas for subsequent electricity generation is always greater than the traditional landfill for aeration times ranging from zero to five years; PW net benefit of gas recovery and use approaches that of traditional landfills after five years of aeration. Greater gas-related monetary benefits are seen for as-built systems because the potential for greater methane collection exists (i.e., collection starts immediately). Gas recovery and subsequent use in retrofit bioreactor systems appears to be less economical than the traditional landfill for aeration periods greater than 0.25 years. When aerating for five years in a retrofit system, the monetary benefit associated with gas recovery and use costs is negligible; collecting gas for electricity generation when aerating for periods longer than five years will likely result in a net cost. The anaerobic bioreactor landfill (no air addition) resulted in approximately 23% more revenue than that associated with traditional landfill gas recovery.

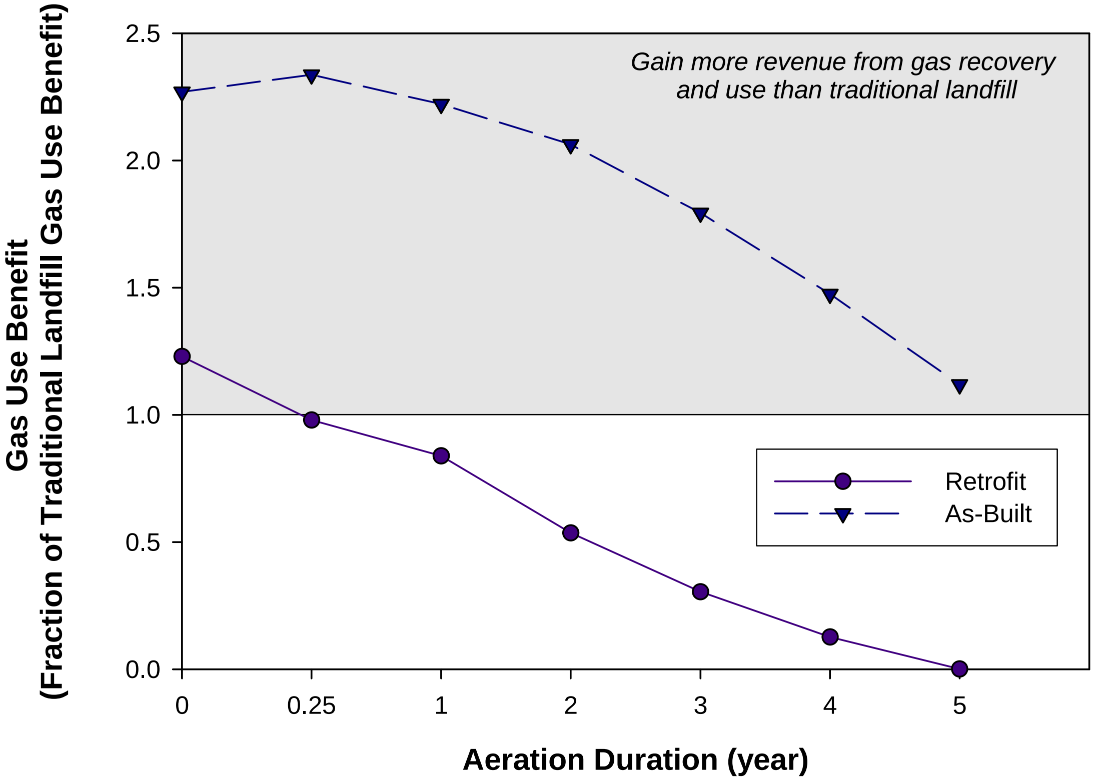
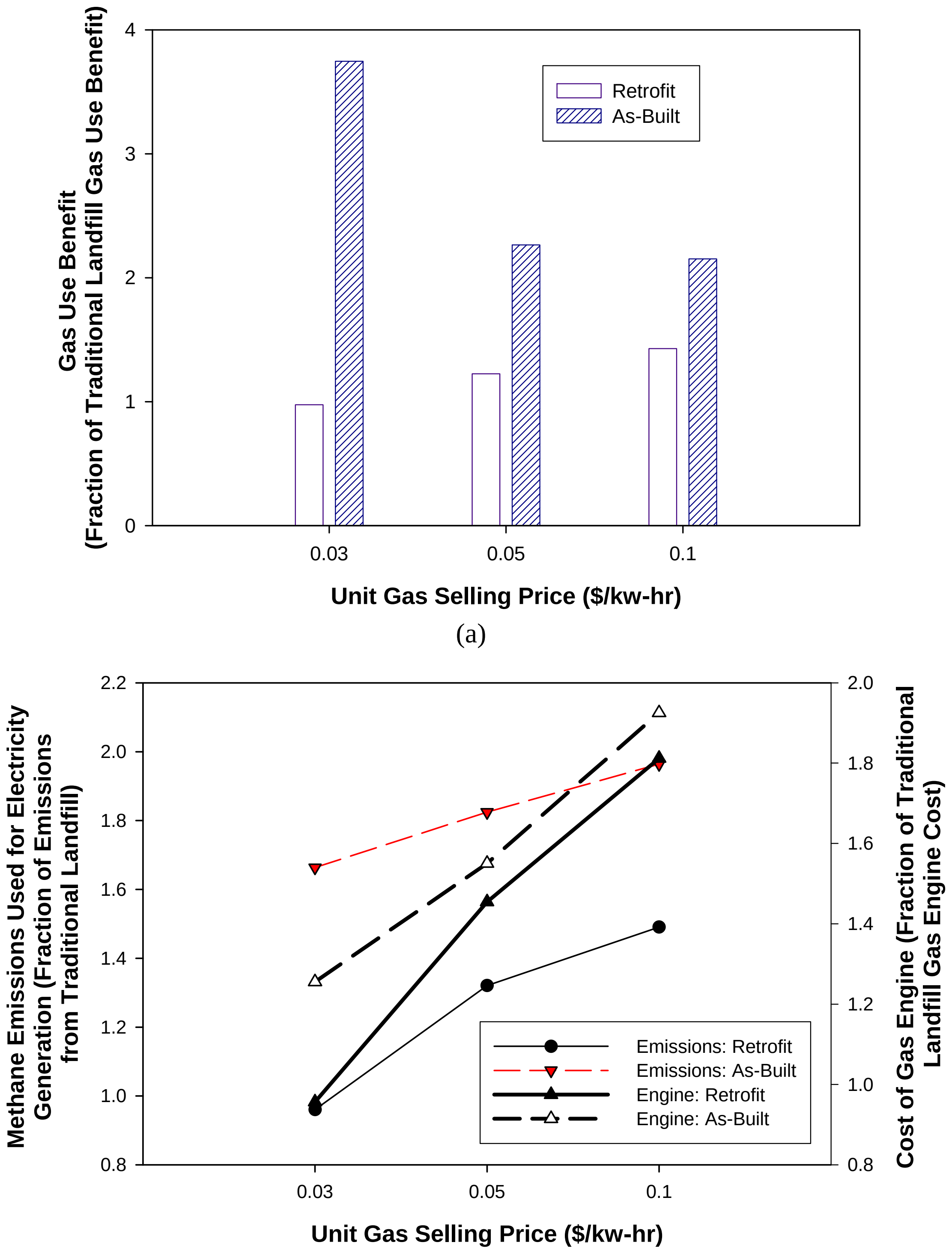


Figure 9.8. The influence of aeration duration on total PW cost of gas recovery and use (as compared to traditional landfills) for base case conditions.

Figure 9.9a presents the influence gas selling price has on monetary gains from gas recovery and use. Because of the matrix used to estimate gas use benefits, traditional landfills benefit more than as-built systems when gas selling price increases. Engine capacity is determined by optimizing potential profit. Although the emissions collected and used for electricity generation increase with gas selling price, so does the size and thus cost of the gas engine (this is illustrated in Figure 9.9b). The difference between the trends associated with both emissions and engine cost for retrofit bioreactor landfills increase with gas selling price, while the opposite is true for as-built systems. As a result, the advantage of as-built landfills is not as greater at increasing gas selling prices. Economic benefits of gas recovery and use are always greater for as-built bioreactors than traditional, but for retrofit the gas selling price must be greater than 0.03 $/Kw-hr before the benefit is greater tan that experienced in traditional landfills.

Factors potentially influencing benefits associated with gas recovery are aeration area, oxygen utilization efficiency, gas selling price, and gas collection and oxygen utilization efficiencies. The influence oxygen utilization efficiency (OUE, i.e., the fraction of oxygen added that is used for carbon destruction) has on monetary benefits associated with recovering methane for electricity generation was evaluated (data not shown). Typical OUEs in bioreactor landfills have not been evaluated, thus a sensitivity analysis was conducted to evaluate how important knowing the value of the OUE is. Results indicate monetary benefits associated with methane recovery and subsequent use decrease as the OUE decreases. A decrease is expected, since, as the OUE increases the remaining methane potential of the waste decreases. Aeration area may also influence costs associated with gas recovery for hybrid bioreactor landfills. In the base case, 25% of the landfill was aerated for each year. Simulations evaluating the influence of aerating different landfill areas were conducted (data not shown). The influence of increasing aeration area is rather insignificant while aerating for one year or less. Changes in aeration area influence the economics of as-built hybrid bioreactors more than those associated with retrofit hybrid bioreactors because the volume of leachate being evaporated increases.



(a)

(b)

Figure 9.9. The influence of gas selling price on gas recovery and subsequent use economics: (a) total gas recovery and use benefits as a function of gas selling price and (b) changes in collected emissions and gas engine costs (as a function of that used for traditional landfills).

9.5.4 Air space recovery

Air space recovery is a benefit associated with all bioreactor landfills and potentially constitutes a major source of revenue. Simulations were conducted (using base case parameters) for various total settlements to evaluate the significance of monetary gains from air space recovery (Figure 9.10). As shown, greater overall monetary gain from airspace recovery exists in as-built landfills (approximately twice), which is not surprising, as monetary gains are realized in real-time during filling and new cell construction is delayed. The simulations depicted in this figure do not include the impact of air addition, however it is assumed that during aeration, more settlement occurs at a faster rate, as aerobic waste degradation rates are generally greater than anaerobic degradation processes. Consequently the earlier reuse of gained space and the time value of money positively influences economics for as-built systems. Retrofit economics will not be influenced by enhanced settlement rates potentially resulting from aeration because, as described previously, monetary gains are experienced at the end of bioreactor landfill operation rather than annually.

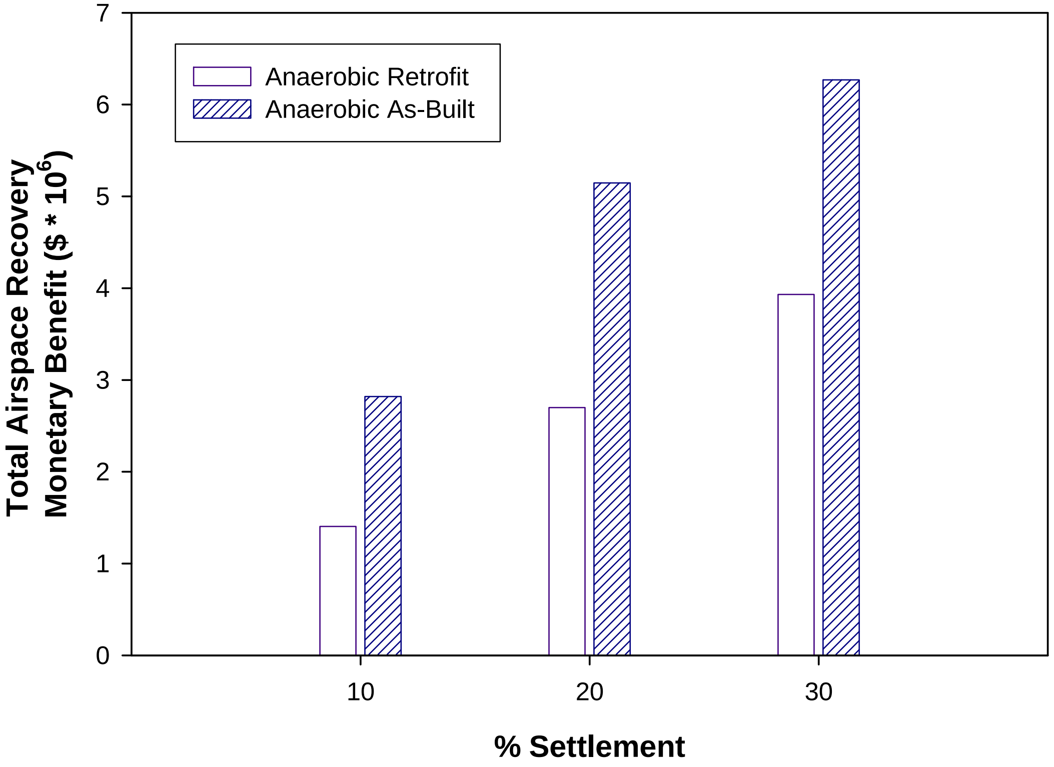


Figure 9.10. Total PW gain associated with air space recovery for different total landfill settlement rates.

9.5.5 Post-closure care periods

Reductions in post-closure care periods have been cited as a potential benefit associated with bioreactor landfills, thus simulations for all landfill scenarios with differing post-closure care periods (10, 20 and 30 years) were conducted. Results are shown in Figure 9.11. As expected, post-closure care costs decrease with decreasing periods. All PCC periods in this study include bioreactor landfill operation and monitoring costs incurred after closure. Thus, costs incurred are greater than those incurred in traditional landfill PCC periods. When the PCC period is reduced by 20 years, the PCC costs decrease by 25 to 30%, which corresponds to only a 2% decrease (~$1 million) in total landfill cost. Thus, reductions in post-closure periods appear to have a minor impact on overall project economics.

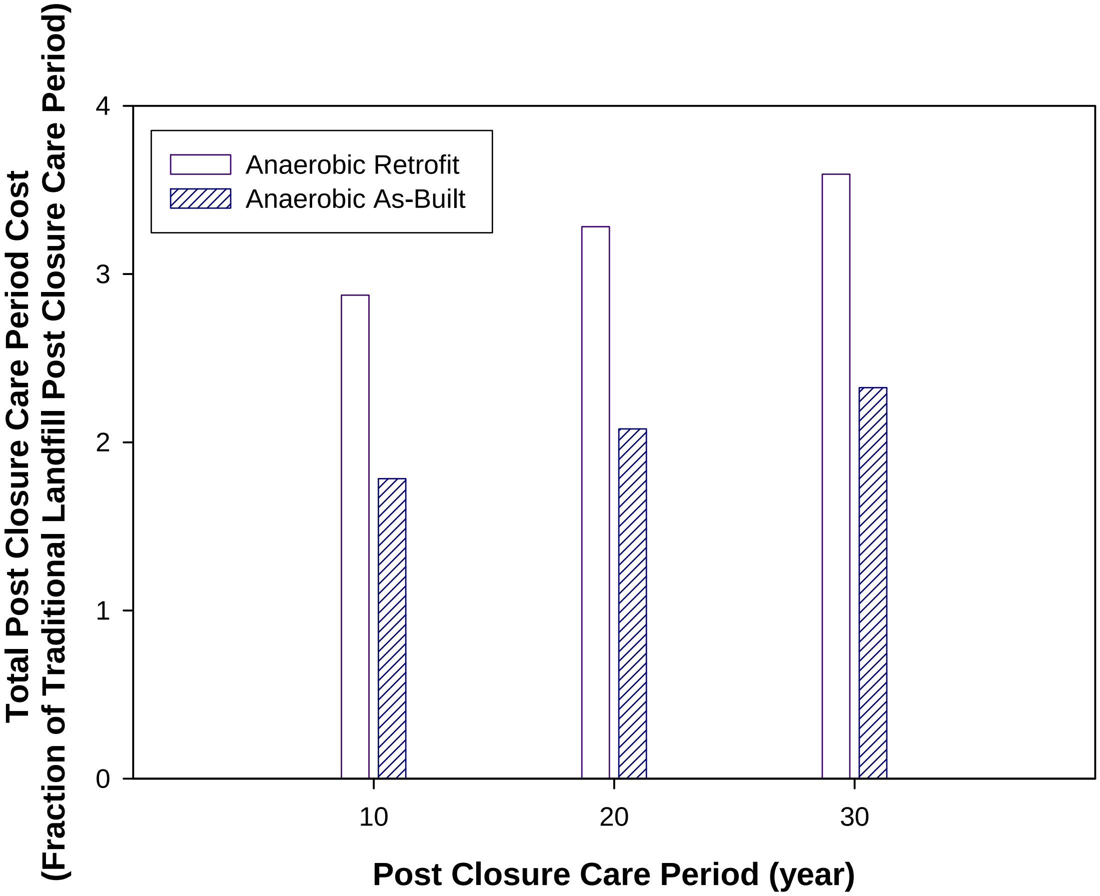


Figure 9.11. The influence of PCC periods on total PCC costs as a fraction of traditional landfill PCC periods (30 years).

9.6 Conclusions

Simulation results indicate the parameters that influence bioreactor economics most significantly are air space recovery, gas recovery and subsequent use to generate electricity, and savings resulting from reduced leachate treatment costs. Air space recovery is dependent on settlement; more research is needed to evaluate achievable settlement and recoverable air space. In addition, the time in which the recovered space is utilized is important to consider when operating a bioreactor landfill, as profits increase if utilized in real-time. Gas recovery and subsequent use also play an important role in reducing the total cost of anaerobic bioreactor landfills. However, when operating a hybrid bioreactor system, gas use is not always economically advantageous. Gas selling price has an influence on the gas-use benefits. Careful analysis of the selling price and expected methane recovery should be conducted when operating hybrid bioreactor landfills. Savings resulting from reduced leachate treatment requirements are also significant.

Based on simulations conducted in this study, both the as-built and aerobic bioreactor landfills have lower PW costs than retrofit bioreactor and traditional landfills. This is primarily because of the profit realized from air space recovery and savings associated with reduced leachate treatment requirements. However, retrofit bioreactor landfills may have the potential to be more economical than traditional landfills if care is taken during operation to ensure maximum profit from air space recovery and leachate treatment savings. Cost savings associated with environmental impact reduction and long term liability reduction have not been estimated for any of the cases. If considering these savings, it is likely all bioreactor landfills will be economically attractive compared to traditional landfills.

9.7 References

Benson, C. H., M. A. Barlaz, D. T. Lane, J. M. Rawe, “Practice review of five bioreactor/recirculation landfills,” *Waste Management*, 27 (2007) 13-19.

Berge, N. B. (2006) “Ammonia Removal in Bioreactor Municipal Solid Waste Landfills,” PhD Dissertation, University of Central Florida, Orlando.

Duffy, D. P., “Landfill Economics, Part II: Getting Down to Business,” MSW Management, July/August, 2005.

Duffy, D. P., “Landfill Economics, Part III: Closing Up Shop,” MSW Management, September/October, 2005.

EPA (2005). Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide. EPA-600/R-05/047.

EPA (1996). Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook. EPA 430-B-96-004.

Chong, T. L., Y. Matsufuji, M. N. Hassan. (2005) “Implementation of the Semi-Aerobic Landfill System (Fukuoka Method) in Developing Countries: A Malaysia Cost Analysis,” Waste Management, 25: 702-711.

Faour, A., D. R. Reinhart, and H. You, (2007) “First-Order Gas Generation Model Parameters for Wet Landfills,” *Waste Management* 27: 946-953.

Gambelin, D. J. D. A. Cochrane, and B. Clister, “Life Cycle Analysis of a Bioreactor Landfill in California,” 3rd Annual SWANA Landfill Symposium, Palm Beach Gardens, Fl, June 22-24 1998.

Hater, G. R., K. E. Young, C. Simpson, and J. M. Harris, “Economics of Eight Scenarios for Landfill Bioreactors as Compared to a Base Case Subtitle D Landfill,” Waste Tech 2001, San Diego, CA February 13, 2001.

Jain, P., Townsend, T., Reinhart, D., Berge, N., Gawande, N. (2005). “New River Regional Landfill: A Full-Scale Bioreactor Landfill Demonstration Project,” World Waste Management, March-April 2005a, pp: 63-70

Jain, P., Powell, J., Townsend, T., Reinhart, D., 2005b. Air permeability of waste in a municipal solid waste landfill. Journal of Environmental Engineering, ASCE, 131(11), 1565-1573.

Jain, P., Powell, J., Townsend, T., Reinhart, D., 2006. Estimating the hydraulic conductivity of landfilled municipal solid waste using the borehole permeameter test. Journal of Environmental Engineering, ASCE, 132(6), 645-652.

Karnik, M. and C. Parry, “Cost Implications of Operating Landfills as Flushing Bioreactors, Proceedings Sardinia 97, Sixth International Landfill Symposium, S. Margherita di Pula, Cagliari, Ital, 13-17 October, 1997.

Reinhart, D. R. and T. Townsend, Landfill Bioreactor Design and Operation, Lewis Publishers, Boca Raton, Florida, 1998.

Read, A. D., Hudgins, M., and Philips, P. (2001). Perpetual Landfilling Through Aeration of the Waste Mass; Lessons from Test Cells in Georgia (USA), Waste Management, 21, 617-629

Rooker, A.P. (2000) “A Critical Evaluation of Factors Required to Terminate the Post-closure Monitoring Period of Solid Waste Landfills,” MS Thesis, North Carolina State University.

Science Applications International Corporation, “State of the Practice for Bioreactor Landfills,” Workshop on Bioreactor Landfills, Arlington, Virginia, September 6-7, 2000 EPA Contract 68-C7-0011, National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268.

Spokas,K., J. Bogner, J.P. Chanton, M. Morcet, C. Aran, C. Graff, Y. Moreau-Le Golvan and I. Hebe (2006)”Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems?” Waste Management, 26(5): 516-525.

Vesilind, W. Worrell, and D. Reinhart, Solid Waste Engineering, Brooks/Cole, Pacific Grove, CA, 2002.

Yolo County Planning and Public Works Department, “A Beneficial Investment in Trash: Controlled Landfill Bioreactor Project,” May 2000 http://www.yolocounty.org/recycle/docs/UCETFreport.pdf.

Attachment

Spreadsheet-based Model for Four Base Cases:

- **Traditional Landfill**
- **As-built Bioreactor Landfill**
- **Retrofit Bioreactor Landfill**
- **Aerobic Bioreactor Landfill**