Enhanced Biodegradation in Landfills

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ABSTRACT

The objective of this paper is to evaluate the effectiveness of leachate recirculation and bioreactor landfills at enhancing biodegradation, and to optimize the operation of a bioreactor. Waste Management has been examining leachate recirculation landfills for several years. Samples of Municipal Solid Waste (MSW) from existing leachate recirculation (LR) landfills were collected and analyzed for several physical and biochemical properties. These parameters of interest were moisture content, pH, density, temperature, volatile solids, cellulose/lignin ratios, and biological methane potential (BMP). Leachate recirculation increased the dry density 55% faster and decreased the BMP 125% more rapidly. Moisture content was the biggest factor influencing overall degradation. Therefore, leachate reciculation effectively increases biodegradation of MSW in landfills.

Waste Management built a pilot-scale bioreactor in Franklin, WI, which was sampled for one year. It contained a bioreactor side and a control side. The volatile solids, cellulose, and BMP degradation rates for the bioreactor were increased by 56%, 87%, and 271% versus the control, respectively. Moisture content was the biggest factor influencing overall degradation.

The column study is designed to optimize three parameters under the control of an operator: moisture content, initial aeration period, and biosolids addition. The optimum moisture content is above 45%, but it is not safe to operate heavy equipment on refuse with greater than 45% moisture. Initial aeration did not speed up the overall degradation, but it did shorten the acidogenic phase. Finally, biosolids did not have a significant effect on degradation rates. The columns maintained an average temperature of 70^{o}F.

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SANITARY LANDFILLS

Introduction

Landfills as we think of them today were first used in the 1930's in the United Kingdom. In the 1940's, New York City and Frenso, California both started the practice of landfilling their waste (Tchobanoglous, 1993). Today, landfilling is the most widely used method of disposal for municipal solid waste (MSW). Sanitary landfills are designed to minimize the risk of health or ecological damage from the disposal of solid waste. The concept of a sanitary landfill came about because of the problems associated with open dumps: fires, rodents, flies, odors, leachate, and explosive gas. Daily cover and compaction were used to reduce the risk of most of these problems, except gas and leachate. However, under subtitle D of the Resource Conservation and Recovery Act (RCRA) of 1976, strict regulations were enacted to deal with leachate and gas production.

Christensen and Kjeldsen (1989) claim that microbial activity will dominate the stabilization of the waste and hence govern the generation of landfill gas and the composition of leachate. Leachate is produced when water is allowed to contact the waste in a landfill, and can contain high levels of suspended solids and chemical oxygen demand. The strength of the leachate depends on the biological activity within the landfill. Sanitary landfills reduce the volume of leachate by not allowing water to infiltrate into the landfill. Furthermore, all leachate produced is collected and treated *ex-situ*.

Landfill gas (LFG) is a result of biodegradation of organic matter in the refuse, and since 50-70 percent of MSW is biodegradable, LFG production can be substantial. The main component of LFG is methane, which is an explosive greenhouse gas. Carbon dioxide is another major constituent in LFG and is also a greenhouse gas. Finally, LFG contains trace amounts of toxic substances. For these reasons, landfill gas and leachate must not be allowed to move off site. Furthermore, LFG is used as a fuel for combustion engines and gas turbines to produce electricity.

Liners

Currently, two types of barriers are used as liners: compacted soil barriers and geosynthetic barriers. A compacted soil barrier is a layer of soil, usually clay, at least two feet thick, and compacted so that the hydraulic conductivity is less than 10^{-7} cm/sec. A geosynthetic barrier is usually a geomembrane, which is a sheet of plastic that is resistant to chemical degradation. The most common type of material used as a geomembrane is high density polyethylene (HDPE), because it is highly impermeable to liquids and vapors.

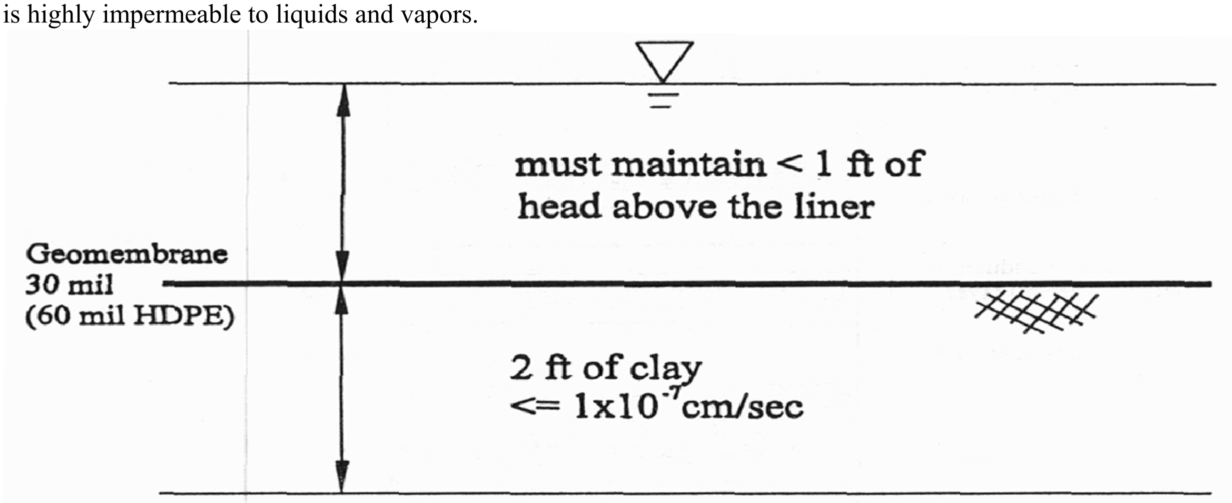

FIGURE 1.1 – CROSS-SECTION OF A COMPOSITE LINER

When a soil barrier and a synthetic barrier are used together it is called a composite liner (see Figure 1.1). Current regulations under RCRA require a double liner, which consists of two composite liners separated by a drainage layer. This is to assure that no leachate is percolating into the groundwater, and that leaks in the primary liner are detected. Furthermore, sanitary landfills are designed so that a maximum of one foot of leachate is allowed to accumulate on the liner.

McBean, Rovers, and Farquhar (1995) propose that a state-of-the-art liner system contains the following components:

1. Optional filter material (soil or geotextile) -- separates the bottom portion of waste from the leachate collection and drainage medium, to reduce clogging of the drainage system. The filter fabric may still clog due to suspended solids, biological growth, and precipitates. Therefore, a high-permeability filter fabric is recommended for use, if one is used at all. Note that geotextiles are sensitive to ultraviolet light degradation if left exposed and therefore must be protected from accidental damage during installation.
2. Drainage Layer -- must have high transmissivity and resist plugging. Gravel is normally used on the bottom and geocomposite for side slopes due to the ease of installation. The gravel should be specified to have a grain diameter larger than 38 mm to minimize biogrowth effects and be meant to resist degradation when exposed to low pH.
3. Protector Layer -- prevents materials in the drainage layer from puncturing the primary geomembrane liner. This layer is usually a thick, needle-punched geotextile (filter fabric).
4. Barrier Layer -- frequently a geomembrane or a natural soil liner or a combination of both. Geosynthetic clay liners (GCL) may be used.
5. Leak Detection System -- identifies leakage from the primary liner system and enables it to be collected and removed. A geonet is preferable to granular materials because it is easier to place on side slopes, and granular materials can puncture a geomembrane. A geonet also offers faster detection of leaks. the secondary containment system is designed so that leachate passing through defects in the primary barrier layer is detected in the secondary leachate collection system (i.e. the detection system) and removed.
6. Secondary Barrier (geomembrane) -- The last defense against leachate escape. Technical requirements are generally the same as for the primary layer.

Leachate Collection

Leachate generated within a landfill moves down to the liner, which is sloped towards the leachate collection pipes. These are perforated pipes surrounded by a gravel layer to filter suspended solids. Once collected by these pipes the leachate is pumped to a storage facility of some type. From there, the leachate is transferred to a treatment facility, possibly a Publicly Owned Treatment Works (POTW).

Caps

Cap systems are designed to prevent water from infiltrating the landfill as well as to prevent gas from escaping. A typical cap design is presented in Figure 1.2 (Reinhart, 1998). The geomembrane used in a cap system must be highly impermeable to vapors, because containment of landfill gas such as methane is very important. The cap must also be able to maintain its integrity while the landfill settles. This requires material with high elasticity.

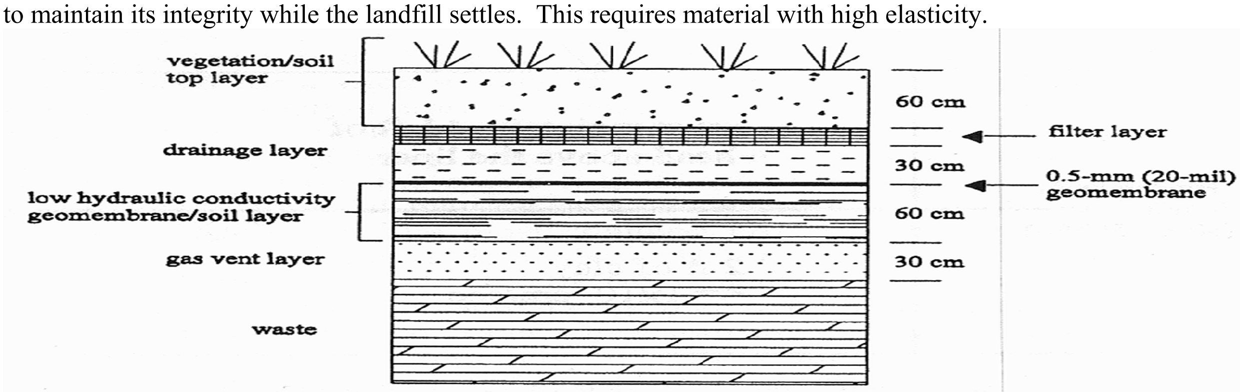

FIGURE 1.2 – LANDFILL CAP DESIGN RECOMMENDED BY EPA

Decomposition Phases

Stabilization of waste in a landfill occurs in five stages: Lag phase, Transition phase, Acid Formation phase, Methane Fermentation phase, and the Maturation phase. Each phase is defined by its characteristic leachate and gas compositions, which are given in Figure 1.3.

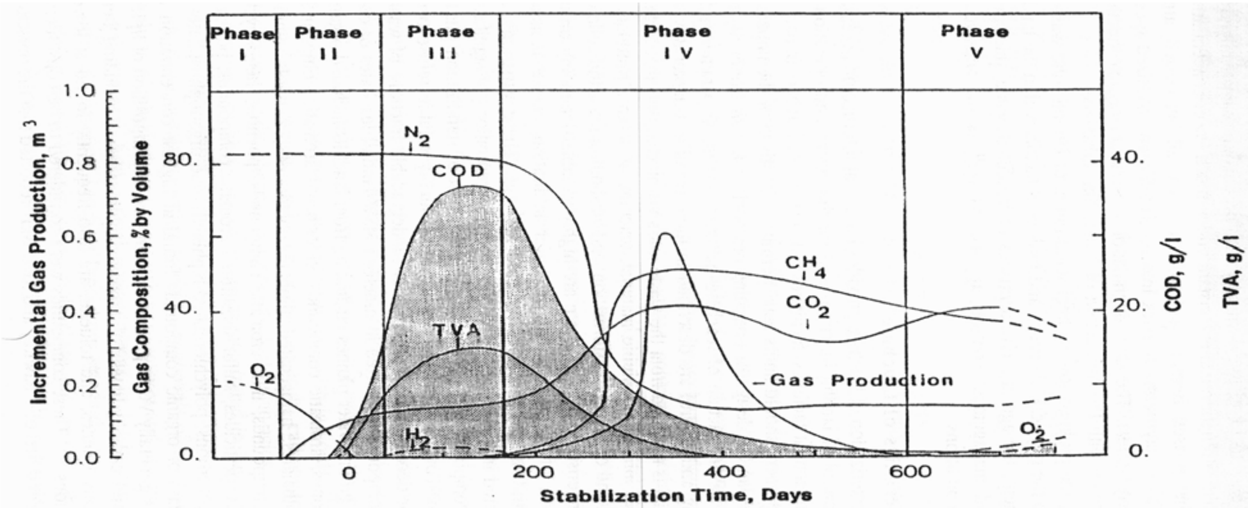

FIGURE 1.3 – FIVE PHASES OF LANDFILL STABILIZATION

The lag phase is the period during which aerobic microbes are becoming established and moisture is building up in the refuse. Once moisture content is sufficient to support microbial growth, aerobic degradation of the refuse begins. This marks the beginning of the transition phase. During transition phase, aerobic degradation consumes the molecular oxygen and conditions go from aerobic to anaerobic. Consequently, a transition toward a reducing environment in which chemical oxygen demand (COD) and volatile organic acids (VOA) begin to form.

$$\text{Degradable waste} + \text{oxygen} \Rightarrow CO_2 + H_2O + \text{heat} + \text{biomass} + \text{Acetic Acid} + \text{Residuals}$$
$$CO_2 + H_2O \Rightarrow H_2CO_3 \text{ (Carbonic Acid)}$$

Increases in COD and VOA signal the beginning of the Acid Formation phase. The VOAs formed during this phase are metabolic intermediates in the overall degradation of organic material in the refuse. These products form much faster than they are consumed, which leads to a build up of VOAs. Therefore, the pH of the leachate is reduced and formerly insoluble metals are mobilized.

The Methane Fermentation phase begins when the organic acids produced in the Acid Formation phase are consumed. The end products of this anaerobic metabolism include CH_4, CO_2, and H_2O vapors.

$$4H_2 + CO_2 \Rightarrow CH_4 + 2H_2O \qquad CH_3COOH \Rightarrow CH_4 + CO_2$$

Consumption of acetic and carbonic acid results in an increase in the pH to around 8. This increase in hydroxide concentration is coupled with the reduction of sulfate to sulfide. Both, sulfide and hydroxide form insoluble complexes with metals. Therefore, metal concentrations in the leachate are significantly reduced.

Once all these reactions go to completion, there is a reduction in biological activity. This signifies the Maturation phase. A characteristic of this phase is very little gas production, because most of the readily degradable organic matter has been degraded. Nutrients and substrate are limited, but there is still slow degradation of the remaining material, which resembles humic matter.

EVALUATION OF LEACHATE RECIRCULATION

Introduction

Laboratory and case studies have concluded that leachate recirculation accelerates stabilization, increases gas production, and decreases leachate strength faster than conventional landfilling. These factors combine to create a more efficient and cheaper method of disposal.

Leachate

Leachate characteristics from recirculating landfills primarily follow the same pattern as sanitary landfills; moving through the five phases. The acid formation phase can be more pronounced in a recirculating landfill. This is because conventional landfills have more dry areas within the refuse, and consequently less leaching opportunity. Thus, conventional landfills produce faster leachate peaks.

Degradation Mechanisms

The fate and transport of compounds in a landfill is determined by conditions in the landfill and the compounds physical and chemical properties. Several natural processes can transform the properties of the compound. These transformations can be Physical/Chemical transformations (such as volatilization, dissolution/advection, precipitation, adsorption, reduction/oxidation, and hydrolysis) or they can be biological transformations (such as mineralization, co-metabolism, accumulation, polymerization).

The Georgia Institute of Technology investigated the fate of 12 primary organic pollutants in a MSW landfill. They showed that reductive dehalogenation is the primary mechanism for the degradation of halogenated organics. Aromatic compounds were also shown to be transformed mainly by reduction and mineralization. In all cases, the study found that recirculating leachate enhanced the conversion of organic pollutants. Leachate recirculation was also found to stimulate methanogenesis (Pohland, 1992).

Although monitoring for metals in the leachate is routinely performed, metal concentrations are usually below detection limits, except for iron and manganese. For recirculating landfills, iron concentrations in the leachate are elevated before closure, while post-closure concentrations decline. On the other hand, iron concentrations at conventionally operated landfills remain constant, but are initially lower than recirculating landfills (Reinhart, 1998). One explanation for this trend is that the added moisture from leachate recirculation increases the mobility of metals initially, however once sulfides and hydroxides begin forming, the metals form insoluble precipitates. With conventional landfilling, the primary removal mechanism is washout.

Final Leachate Treatment

By the time a bioreactor is stabilized, the leachate has been recirculated many times, thus most of the degradable material in the leachate has been degraded. The remaining constituents in the leachate consist of nondegradable organic and inorganic compounds such as iron, chloride, and ammonia. Since there is little degradable organic matter, even less nutrients, and potentially toxic inorganics, biological treatment options may be difficult to maintain. Therefore, physical chemical processes such as ion exchange, filtration, precipitation, adsorption, and reverse osmosis are more likely choices. With pretreatment, discharge into a POTW can be an option. One such pretreatment option would be to add nutrients and high lime to reduce metal concentrations (Robinson, 1985).

Landfill Gas Generation

Leachate recirculation greatly increases the production of landfill gas (LFG) relative to conventional landfills. Researchers working at the landfill in Alachua County, Florida used parallel recirculating and conventional landfill cells to measure gas production rates. They report a doubling of production rates for the recirculating cell relative to the conventional cell (measured by surface emissions). Measurements of the biological methane potential (BMP) show a 50 percent reduction for the recirculating cell (46 percent wet basis) and negligible reduction for the dry cell (29 percent wet basis) over the same period (Lewis, 1995). Increasing methane production allows for increased recovery. Therefore, less volume over the life of the landfill will be released into the atmosphere. Tchobanoglous maintains that energy recovered from LFG is usually in the form of electricity (1993). Internal combustion engines (50kW to 5MW) and gas turbines (1MW to 50 MW) are the main technologies used to generate electricity from LFG.

BIOREACTOR DESIGN

Introduction

A bioreactor landfill in the United States must comply with federal regulations (specifically RCRA regulations) just as a sanitary landfill. Therefore, design of a bioreactor landfill is merely an adaptation of a sanitary landfill. These adaptations must be able to accommodate the added leachate and gas generated as well as allow infiltration and leachate reintroduction. Additional leachate storage and piping, a leachate pumping station, and some type of leachate distribution system are necessary components to adapt to bioreactor operation. This section describes current bioreactor design parameters.

Liner and Leachate Collection System

Some states require only a single composite liner (like the one in Figure 1.1) for MSW landfills, but it is advisable to use a double composite liner because of the added leachate flow. A critical element of the leachate collection system is the drainage layer, which consists of perforated pipes embedded in a layer of highly permeable soil or gravel. This layer conveys the leachate from the liner to the pumping station to be recirculated.

Clogging of the drainage layer, which is caused by biological growth, precipitation, and sedimentation, is a major concern. Soil or geotextile layers are used to filter the leachate entering the drainage layer, but even the filters themselves can become clogged. Clogging is most likely during the acidogenesis phase. Precipitation of metals and increases in organic substrate create a favorable environment for clogging.

Giroud (1996) makes the following recommendations for filter selection to minimize the risk of clogging:

- sand filters and nonwoven geotextile fibers should not be used,
- if a filter is used, a monofilament woven geotextile (perhaps treated with biocide) with a minimum filtration opening size of 0.5 mm and a minimum relative area of 30 percent should be selected, and
- the drainage medium should be an open-graded material, such as gravel, designed to accommodate particle and organic matter passing through the filter.

The drainage pipes should be sized to carry the excess flow experienced with leachate recirculation. The expected flows should be predicted using a mathematical model such as the Hydrologic Evaluation of Landfill Performance Model (HELP). HELP is the most widely utilized modeling program for leachate prediction (Reinhart, 1998).

Leachate Storage

There are two functions of leachate storage: storage in times of excess leachate and a source of leachate in dryer times. Minimizing *ex situ* treatment of leachate is a priority when designing storage facilities. This is particularly important in early stages of landfill operation, because large volumes of storm water can be collected in areas of the landfill that are not covered with waste. Undersized storage facilities may lead to costly *ex situ* treatment, excess head on liners, or reduction of moisture content due to lack of available leachate during droughts.

Baetz and Onysko (1993) recommend sizing storage vessels based on two circumstances: no precipitation (compensate for leakage through the liner) and peak storm events (based on IDF curves and landfill area). The volume needed to recirculate when there is no precipitation (V_1) is calculated using the leakage rate of the composite liner:

$$V_1 = Q_l\, t_{ie}$$

where: V_1 = volume needed to compensate for leakage, L^3
t_{ie} = design precipitation interevent time, T
Q_l = leakage rate of the composite liner, L^3/T

The volume required to accommodate a peak storm event (V_2) is given by the following equation:

$$V_2 = i_d\, P\, A\, t_e$$

where: V_2 = volume of leachate produced by a peak storm event, L^3
i_d = design precipitation intensity, L/T
P = percolation factor
A = area, L^2
t_e = duration of precipitation event, T

The percolation factor is the fraction of rainfall that percolates out the base of the cover. The design precipitation intensity is extrapolated from an Intensity-Duration-Frequency (IDF) curve shown in Figure 1.4.

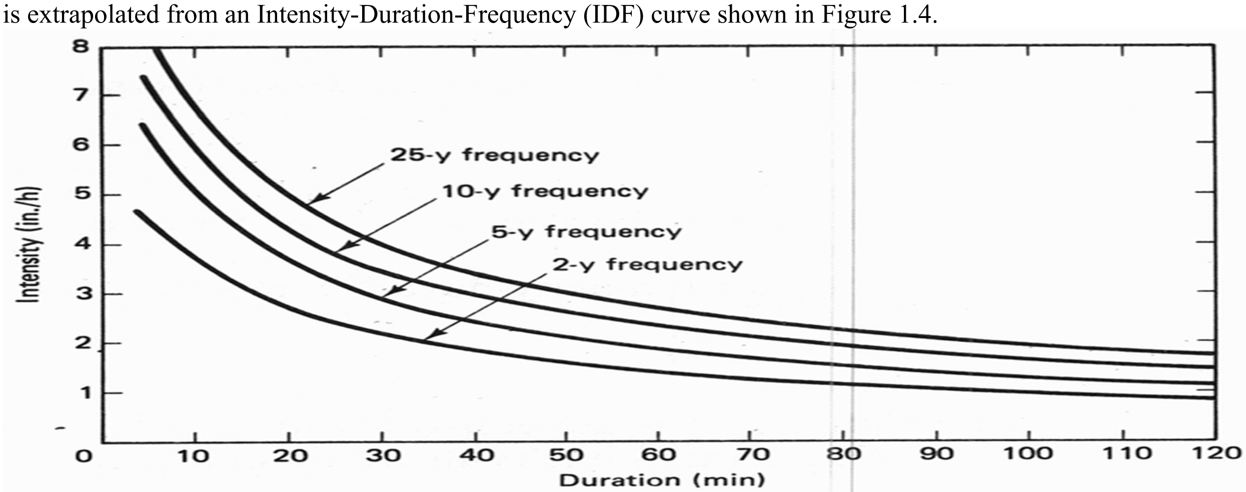

FIGURE 1.4 – INTENSITY-DURATION-FREQUENCY CURVE

For a chosen storm frequency and duration, the intensity can be determined. For example, the design could be for the worst storm in 20 years that lasts 24 hours, thus the duration (t_e) would be 24 hours and the frequency would be 20 years.

Leachate Reintroduction Systems

There are many different methods of distributing leachate or water among refuse in a landfill. Currently utilized methods include prewetting, surface ponds, spraying, horizontal and vertical pipes. These methods have various advantages and disadvantages, which are best summarized in Table 1.1 from Reinhardt and Townsend (1998).

Prewetting of Waste
Prewetting of waste is simple and evenly distributes moisture. Furthermore, prewetting greatly increases compaction of the waste. Leachate from previously filled cells can be used in prewetting. Water tankers or fire hoses can be used to distribute the moisture. Evaporation during prewetting is another benefit if leachate is being utilized.

TABLE 1.1 ─ COMPARISON OF FREQUENTLY USED LEACHATE RECIRCULATION DEVICES

Recirculation Method	Disadvantages	Advantages
Prewetting	• Labor intensive • Incompatible with closure • Enhances compaction (may interfere with routing)	• Simple • Uniform and efficient wetting • Promotes evaporation
Vertical injection wells	• Subsidence problems • Limited recharge area • Interference with waste placement operations	• Relatively large volumes of leachate can be recirculated • Easy to construct during and following waste placement • Low cost materials • Compatible with closure
Horizontal trenches	• Potential subsidence impact on trench integrity • Potential biofouling may limit volume • Inaccessible for remediation	• Low cost materials • Compatible with closure • Large volumes of leachate can be recirculated • Unobtrusive during landfill operation
Surface ponds	• Collect stormwater • Floating waste • Odors • Limited impact are • Incompatible with closure	• Simple construction and operation • Effective wetting directly beneath pond • Leachate storage provided
Spray irrigation	• Leachate lowing and misting • Surface precipitation leads to decreased permeability • Cannot be used in inclement weather • Incompatible with closure	• Flexible • Promotes evaporation

Surface Ponds
Surface ponds are basically carved into the waste. They are simple, but not very efficient. They collect stormwater and do not evenly distribute moisture. Furthermore, floating waste and odors are possible problems with surface ponds. Finally, the volume of the pond takes up valuable landfill space that could be used for refuse.

Spraying
Spraying of leachate over the surface of a landfill is a simple and efficient method of distribution, however many problems have led many states to ban this method of application. One such problem is blowing of leachate off-site. This demands extremely large buffer areas around a landfill, which is not feasible. The Seamer Carr Landfill in England reported the development of a solid hard-pan over the surface caused by precipitation of leachate constituents when exposed to the atmosphere (Robinson and Maris, 1985). Spraying also offers many benefits. It is a very manageable system that can be moved easily to evenly distribute leachate. Also, spraying provides the largest volume reductions of all the methods currently utilized.

Horizontal Recharge Trenches
Horizontal trenches are the most commonly used method of reintroducing leachate into a landfill. Horizontal trenches consist of perforated pipes installed horizontally across the landfill and surrounded by a layer of permeable material, usually gravel or shredded tires. They can effectively introduce large volumes of leachate, but the trenches may become clogged from biological growth. Leachate may be fed by gravity or pumped through the piping system. These systems are

easily constructed and tend to be quite durable. Horizontal trenches can be used after closure, but the cover must be constructed around the piping system.

Vertical Injection Wells

Vertical injection wells are large, perforated concrete pipes that are placed vertically into the refuse. These pipes are divided into sections, in which leachate is pumped to disperse radially out from the wells. To prevent leachate from not passing through the waste, the bottom section of pipe is not perforated. Wells are fed by tanker trucks or leachate is piped into the wells continually. If rest periods are provided, then it has been shown that infiltration rates are increased. Problems with this type of system include tearing of bottom liners and hindrance of waste placement and compaction during active landfilling.

Final and Intermediate Caps

According to subtitle D of RCRA, the final cap must prevent the infiltration of rainwater into a closed landfill. Therefore, most landfills are only receiving moisture while being filled, or during pre-closure. Since this phase usually only lasts for 2-5 years, most landfills are below optimum moisture content for biological activity. Furthermore, biological degradation consumes a lot of the moisture already present.

In order to operate a landfill as a bioreactor, a permeable cap must be used as an intermediate step before final closure. This intermediate cap would allow limited infiltration as well as leachate recirculation. Another benefit of an intermediate cap is that it is less delicate and more accommodating to subsidence.

A potential problem with intermediate covers is efficient gas collection. Since these caps are permeable, gas is not controlled within the landfill. Therefore, getting regulators to accept these intermediate covers will take additional study.

Landfill Gas Management

Due to the increased gas production in bioreactors, proper management of LFG is crucial. Effective collection and efficient utilization are primary goals of a LFG management program. Horizontal trenches, like those used for recirculation, are the most popular method of gas collection for bioreactors. Current operations use one or two trenches per lift of refuse. Studies have shown that the highest gas production occurs around leachate reintroduction sites, therefore leachate injection trenches are being used as gas extraction trenches as well. However, ponding of leachate at the bottom of these trenches can reduce infiltration of gas into the trench (Lewis, 1995).

Construction Costs

Leachate recirculation provides effective treatment of leachate at a minimal cost. Since most of the components used in recirculation are already required for conventional landfilling, the additional cost is insignificant. For example, the construction costs for recirculation at DSWA landfills are between \$10,000 and \$200,000, while on-site treatment is estimated to be between \$1,000,000 to \$6,000,000. The major expenses of recirculating leachate are the transmission lines and reintroduction devices (Reinhart, 1996).

LANDFILL BIOREACTOR OPERATION

Introduction

Operating a landfill as a bioreactor requires close monitoring and control of conditions within the landfill. Unlike sanitary landfills, bioreactor landfills have many parameters that the operator can adjust in order to increase stabilization and gas production. Some of these parameters are moisture content, frequency of recirculation, waste placement, temperature, addition of nutrients, microbial inoculation, and addition of buffers. Proper management of these and other parameters can lead to very quick stabilization of waste and high methane production rates.

Waste Characterization

Composition

The composition of MSW is constantly changing as population increases, lifestyles change, and regulations are enacted. Future trends that will effect waste composition must be foreseen in order to properly design a bioreactor landfill. The composition of MSW affects the products and rate of degradation. For example, increases in the use of plastics would increase the non-biodegradable fraction of the waste, which would decrease the amount of methane produced. On the other hand, increased recycling would increase the organic fraction, which would increase the methane production. Preprocessing allows for control of waste composition and produces a homogeneous waste.

Physical Properties

Two physical properties that are of primary concern are the following: particle size and in-place density. In-place density is controlled by compaction, either in the landfill or by baling the waste. Compaction is accomplished in the landfill by running heavy equipment over the waste a number of times (3 to 4 is optimal). Typical densities from field compaction range from 800 to 1400 lbs/yd^3. Baling the waste can increase the density of waste up to 1500 lbs/yd^3. Increased density saves landfill space, reduces settlement, and reduces cover material needed. However hydraulic conductivity is reduced, and leachate is more likely to travel through channels within the refuse. Therefore, it is advisable to `reduce compaction in order to increase moisture distribution and degradation rates (Tchobanoglous, 1993).

Particle size also affects the routing of moisture within a landfill. Reducing particle size allows more surface area to be in contact with water thus facilitating biological and chemical degradation. Shredding produces a more uniform refuse, which results in even settling and greater compaction under equivalent pressure. Another advantage to shredded waste is that it does not require daily cover, which can disrupt moisture flow. Shredding is expensive and is not currently used at most MSW landfills. However, the added gas production and decreased stabilization times may make it cost effective in the long run (Reinhart, 1998).

Oxidation Reduction Condition

The redox potential within a landfill determines the mechanism of waste degradation. Generally, high redox potential (aerobic conditions) causes accelerated degradation of waste, but air must be supplied which increases operational costs. Furthermore, aerobic degradation has a potential to produce fires because of the excess heat and oxygen. On the other hand, anaerobic degradation (low redox potential) has many benefits such as:

- methane is produced (valuable energy source)
- degradation of resistant compounds for which aerobic pathways don't exist (chlorinated solvents)
- conditions are easily maintained.

A two-stage process, which consists of an aerobic and anaerobic phase, has recently been suggested by several researchers. Aerobic conditions in the first stage would be maintained by supplying air to the landfill. The aerobic microorganisms in the landfill would quickly metabolize the readily degradable organics first. Once the readily degradable material has been metabolized, the air supply would be shut off and anaerobic conditions would become established. The more resistant material would slowly be degraded by anaerobic mechanisms.

This two-stage process would combine the advantages of both aerobic and anaerobic mechanisms, while eliminating some of the disadvantages. The overall stabilization rate is increased, while shortening the acidogenic phase which increases methane production. Another benefit is that anaerobic pathways that can degrade resistant chemicals such as PAHs are still possible. Although more research is necessary, this process appears to be the most efficient use of redox potential to accelerate degradation.

Moisture Content

Addition of moisture enhances methanogenesis, nutrient transport, pH buffering, and microbial degradation. Leachate recirculation is an efficient method of increasing moisture content. The advantages of leachate recirculation include control of moisture content, reduction of leachate through evaporation, and leachate treatment. Rotating areas of introduction of leachate with rest between introduction episodes has been shown to be the most effective method of recirculation (Reinhart and Townsend, 1998). This is because saturation is detrimental to methanogenesis. However, once methanogenesis is established, recirculation frequency may be increased.

Lysimeter studies of the effect of moisture content on waste degradation recommend a minimum of 25 percent (wet basis) and 40 to 70 percent for optimum degradation. However, operating landfills greater than 35 percent moisture content can cause problems with equipment moving over the refuse (Gurijala, 1993).

Biological Enhancement

Buffering
Kasali and Watson-Craik claim methanogens are only active between a pH of 6.8 and 7.4, thus control of pH is important is establishing methanogenesis (1988). Buffering is particularly important in early stages of degradation; when excess acids are produced and pH levels can drop quickly. Since low pH is typically the problem, the alkalinity is increased by adding lime or sodium hydroxide to the leachate during storage.

Sulfate
Inhibition of methanogenesis by sulfate has been observed in a variety of environments. Sulfate-reducing bacteria out compete methanogenic bacteria for electron donors like acetate and H_2. Therefore, methanogenesis is hindered in sulfate-rich environments like construction and demolition debris landfills, which contain gypsum.

Nutrients
Nutrient requirements (both organic and inorganic) are typically met by the organic fraction of MSW. Phosphorus has been limiting in later phases of degradation. In most cases, nutrients do not increase degradation rates and therefore are not typically added.

Temperature Control
The microorganisms that carry out degradation of waste in a landfill prefer a certain temperature. In general, degradation rates increase with temperature up to an optimum temperature, specific for that particular microbe. Gurijala (1993) reported 40^{o}C as optimum with significant inhibition over 55^{o}C. Temperature control is very difficult and is currently not widely practiced because of economic inefficiency.

Inoculation
Inoculation has typically been done by adding biosolids from a wastewater treatment plant. Results from studies evaluating the effects of such additions have been inconsistent. Reinhardt and Townsend (1998) claim that any effect may be due to moisture addition or buffering more than seeding. Due to the varying effects and difficulty of handling, biosolids are not commonly added.

Another method of establishing microbial populations is to place fresh waste over decomposed wastes. Studies have shown that the old refuse can stimulate methanogenesis and is more effective at treating leachate.

Intermediate Cover

Low permeability cover material prevents uniform distribution of recirculated leachate. Therefore, dry areas just below these covers are not degraded, while ponding and side seeps can occur in other areas. To prevent heterogeneous movement of moisture, high permeability cover materials should be used, such as foam, carpet, mulch, geotextiles, or sandy soil. Geotextiles and carpet should be removed before adding the next lift.

Settlement

Settlement can cause problems for recirculation devices as well as for final caps. Leachate reintroduction pipes should be flexible materials. Internal trenches and wells can also be impaired by uneven settling or horizontal shifts. In many cases, trenches will still effectively distribute leachate after a pipe break, however filler material is crucial. If problems due occur, then repair of these systems is expensive.

The cap system for a bioreactor landfill should have relatively thick layers and be very flexible. If the integrity of the cap is maintained, then slope corrections and grading to account for settlement is inexpensive. However, if the cap does not maintain its integrity, repairs are once again very costly.

Monitoring

McBean et al. (1995) states that the intent of a monitoring program is to determine the degree to which a landfill and any associated containment system is functioning in accord with the design objectives. Monitoring is especially important for bioreactor landfills because of the added process control and lack of experience in their operation. Standard methods for conducting most of the analyses necessary are available, however gas flow rate and *in situ* waste characteristics are difficult to measure.

Leachate characteristics are mainly monitored to determine the extent of stabilization. Thus, the leachate parameters monitored are reactants and products of biological and chemical reactions. For instance, metals, ammonia, and conductivity are important parameters when assessing maturity because they are end products of final degradation reactions.

EPA SEMINAR: LANDFILL BIOREACTOR DESIGN AND OPERATION

In 1995, the EPA held a conference in Wilmington, Delaware on the subject of municipal solid waste landfill bioreactors where thirteen papers were presented. These papers offer the latest findings on bioreactor design and operation. They are written from a range of perspectives including regulatory, owner/operator, and international. The rest of this section describes some of the topics presented at the conference.

Leszkiewicz and McAuley characterized the impact of incremental closure and installation of final, impermeable covers on biological activity within the landfill. They assert that because of significant microbial water consumption, the water requirements for nearly complete biodegradation of organics are greater than previously estimated. Furthermore, if moisture content of the refuse drops below a certain level at any time during degradation, then all further microbial activity ceases.

In his presentation, Campbell contended that in order to enhance biodegradation of the waste, the following factors must be optimized:

- reduced particle size
- homogenized waste
- ample moisture
- uniform moisture movement
- temperature
- removal of leachate and gaseous products of degradation

Augenstein and Yasdani describe what measurements are necessary to properly operate a bioreactor landfill and how to best obtain these sometimes difficult measurements. For example, gas generation is a good index of decomposition. Bioreactor gas recovery rates can vary over time scales from hours to years, however, and are often difficult to predict. Therefore, wide instrumentation range, and cumulative measurement, are necessary.

Koerner and Koerner suggest not using filters for the drainage layer. These filters become clogged with microbial growth, which is accelerated in bioreactor landfills. However, they also recommend long-term laboratory studies using the site specific materials before implementing this technique.

Watson describes how to incorporate techniques into lab-scale and full-scale bioreators. These techniques include: complete mixing, moisture addition, aeration or oxygen depletion, pH adjustments, temperature control, nutrient addition, accurate measurement, and accurate and representative sampling.

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Chapter 2

EVALUATION OF BIOCHEMICAL AND PHYSICAL DATA TO DETERMINE THE IMPACT OF LEACHATE RECIRCULATION

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ABSTRACT

The objective of this paper is to evaluate leachate recirculation's effectiveness in enhancing the stabilization of a landfill. Waste Management, Inc. has been evaluating leachate recirculation landfills for several years. Samples of Municipal Solid Waste (MSW) from existing leachate recirculation (LR) landfills were collected and analyzed for several physical and biochemical properties. The parameters of interest were moisture content, pH, density, temperature, volatile solids, cellulose/lignin ratio, and biochemical methane potential (BMP). Leachate recirculation increased the dry density at a rate of 263-lbs/cu yd/yr versus 170-lbs/cu yd/yr for the control. The first-order BMP degradation rate also increased from 0.1922 yr^{-1} to 0.4329 yr^{-1} through leachate recirculation. Moisture content was the biggest factor influencing overall degradation. The data shows that leachate reciculation effectively increases biodegradation of MSW in landfills.

INTRODUCTION

Waste Management, Inc. sampled seven landfills throughout the United States during 2000. Four landfills contained leachate recirculation (LR) as well as control (non-recirculation) sites. These landfills were the Atlantic Recycling and Disposal Landfill in Waverly, Virginia, Spruce Ridge Landfill in Glencoe, Minnesota, Middle Peninsula Landfill and Recycling Facility in Glenns, VA and Evergreen Landfill in Northwood, Ohio. The Atlantic and Middle Peninsula landfills were approximately three years old at the time the samples were collected. The Spruce Ridge and Evergreen landfills were six and seven years old, respectively. Two methods were used for leachate recirculation. Atlantic and Spruce Ridge landfills incorporated dedicated horizontal piping trenches filled with rubber tire chips and intermittent surface application at the working face. According to field reports this results in the most uniform distribution of liquid. Middle Peninsula utilized the same collection system for leachate recirculation and gas collection, which requires less landfill space. Evergreen used a continuous rubber tire chip layer over the recirculation area connected to stand pipes for achieving complete surface coverage. The Riverbend landfill in McMinnville, Oregon did not recirculate leachate, but was selected as a "wet site" based upon annual precipitation. Riverbend contains three cells with ages of 2, 5, and 11 years. This site was sampled to provide a long-term trend for the parameters of interest.

Addition of moisture enhances methanogenesis, nutrient transport, pH buffering, and microbial degradation. Leachate recirculation is an efficient method of increasing moisture content. The advantages of leachate recirculation and controlling also include reduction of leachate through evaporation and *in-situ* leachate treatment. Rotating areas of leachate recycle with rest periods between introduction episodes has been shown to be the most effective method of recirculation (Reinhart and Townsend, 1998). This is because methanogenesis is limited for a waste mass at its maximum water holding capacity. However, once methanogenesis is established, recirculation frequency may be increased.

Lysimeter studies of the effect of moisture content on waste degradation recommend a minimum of 25 percent (wet basis) and 40 to 70 percent for optimum degradation. However, for operating landfills greater than 35 percent moisture content can cause problems with equipment movement over the refuse (Gurijala, 1993).

This paper focuses on the biochemical and physical changes observed between four landfills with both control and leachate recirculation areas. The objective is to achieve rapid stabilization of the MSW through leachate recirculation. Analyses of the MSW were used to evaluate the level of stabilization. Biochemcial methane potential (BMP) is a particularly useful analysis, since it is a measure of the amount of methanogenic degradation still possible from a sample.

METHODS

Sampling is nearly always considered the greatest source of error for landfill studies. Sampling was accomplished using a drill rig outfitted with a 36-inch bucket auger to collect refuse. Ten-pound samples were collected from the top, middle, and bottom of each ten-foot section and shipped to Virginia Tech, Blacksburg, VA in coolers.

The MSW wet density was obtained in the field using a realistic approach. Each ten-foot segment was placed into a tared roll-off box and weighed. This weight divided by the volume ($\pi r^2 h=\pi*1.5^2*10=70.69\ ft^3= 2.62\ yd^3$) gives the wet field density. The dry density was calculated from the wet density and the measured moisture content. Both wet and dry densities are reported in pounds per cubic yard (lbs/yd^3).

The method for measuring moisture content was adapted from standad method 2540-B using between 500 and 1000 grams of wet, unshredded MSW, which was dried in an aluminum pan at 105°C to a constant weight, usually less than 2 days (APHA et al., 1995). The weight lost by evaporation of water is divided by the original sample weight to give the moisture content, reported as a percent by weight.

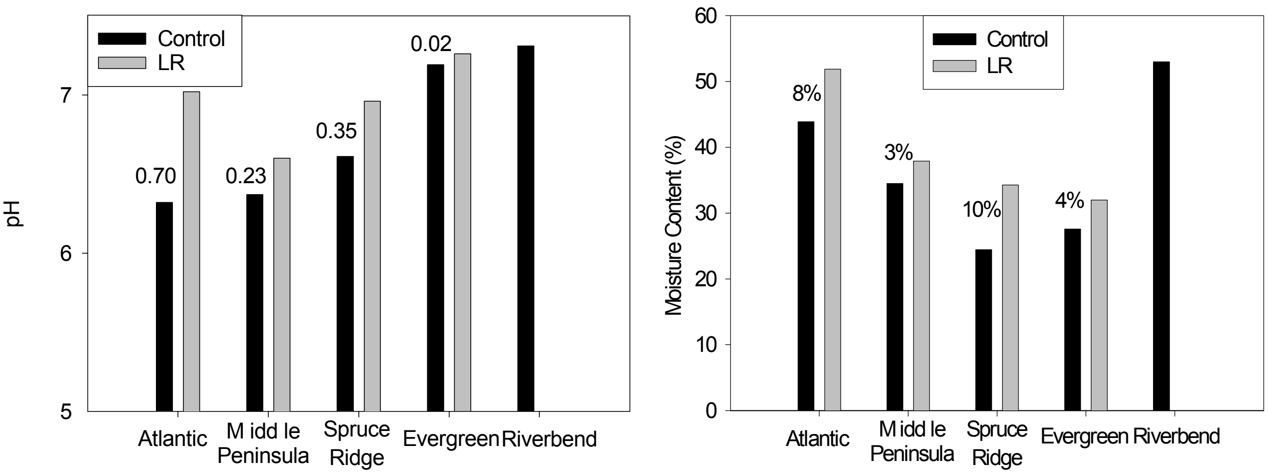
The pH was obtained by mixing 50% (% by weight) wet, unshredded MSW and distilled water in a one-liter glass beaker. The mixture was allowed to come to equilibrium at 20°C (approximately 5 hours), and a calibrated pH electrode was placed into the liquid until a stable reading was obtained.

Shredding was performed in two stages. Dry samples were initially chopped in a bench top blender. Then, samples were put through a Thomas Intermediate Wiley Mill with a 10-mesh screen to achieve a powder-like consistency. Nongrindables, such as rocks, nails, etc., were removed and weighed.

The volatile solids were measured by standard method 2540-E (APHA et al., 1995). One to two grams of dry, milled refuse in an aluminum weighing pan, which was then placed in a muffle furnace at 550°C for approximately 20 minutes (until no additional weight loss was measured). The percent by weight of refuse that was lost is reported as volatile solids.

The cellulose and lignin analysis was taken from ASTM E 1758-95[e1] (1995). A sample size of 300 mg of dry, milled MSW was also used for this measurement. The cellulose was hydrolyzed into glucose monomers in two stages using sulfuric acid. First, the samples were digested in three milliliters of 72% sulfuric acid in a water bath at 45°C for two hours. Second, the samples were transferred to 250 mL septa bottles using 84 mL of nanopure water and autoclaved for one hour at 121°C and 15 psi. The samples were then filtered using standard TSS glass fiber filters. The volatile suspended solids (combusted at 550°C) remaining after hydrolysis was considered lignin. The filtrate was then neutralized using powdered $CaCO_3$. The glucose was quantified using HPLC with a refractive index detector and HPX-87C carbohydrate column.

Biochemical methane potential (BMP) was modified from a procedure developed by Barlaz (Barlaz, 2000). Two grams of dry, shredded MSW were added to a 250 mL Boston round septa bottle. Then, 100 mL of revised anaerobic media was added to each bottle. The media was made following Barlaz's method except for two modifications. The vitamin solution was not included, and anaerobic digester biosolids were added as an inoculum at 10% by volume (Stinson and Ham, 1995). The bottles were incubated inverted for 45 days at 35°C. One-liter Teflon gas sampling bags were connected to each bottle at the end of the incubation period for twenty minutes while agitating the bottle to relieve excess pressure. A 100-microliter sample was taken from the gas-sampling bag and injected into a GC with a carbosieve packed column and a flame ionization detector (FID). The volume of gas in the gas-sampling bag was measured using a 60 mL plastic syringe. This test was run in triplicate with one blank for every six bottles. The amount of methane measured in the blanks was deducted from that of the samples. The BMP was reported in units of milliliters of methane per gram of dry MSW at STP (mL CH_4/g).



(a) (b)

FIGURE 2.1 – (a)THE pH AND (b) MOISTURE CONTENTS OF THE FOUR LANDFILLS WITH CONTROL AND LEACHATE RECIRCULATION SITES

RESULTS AND DISCUSSION

Moisture Content and pH: The pH for both control and leachate recirculation cells increased with age. Additionally, the pH for the LR cells was always higher than that of the control cells as shown in Figure 2.1(a). The increase in pH is most likely due to the generation of alkalinity by denitrifying bacteria in the form of ammonia. The increased degradation of organic acids in the LR cells also contributes to the higher pH values. The moisture contents of the LR sites were always higher than that of the control sites (Figure 2.1(b)). However, the moisture increases for Middle Peninsula and Evergreen were only 3% and 4%, respectively. The main advantages of leachate recirculation are that moisture content is increased and moisture is distributed more evenly, both of which enhance biodegradation. If the differences in moisture content were greater, then leachate recirculation would have been more effective.

Volatile Solids: The volatile solids (VS) content decreased with time for both the control and LR sites. Based on the linear regressions shown in Figure 2.2(a), leachate recirculation showed only a 2% increase in the average rate of degradation from 9.1495 %VS/yr to 9.3385 %VS/yr. However, the average value of volatile solids for a LR site was 21% less than that of the control. The data suggests that much of the degradation of VS took place over the first three years of leachate recirculation.

Cellulose/Lignin: Cellulose is a polysaccaride that is readily degradable, while lignin is a recalcitrant material that can inhibit cellulose degradation (Stinson and Ham, 1995). Thus, as the landfill stabilizes, the cellulose/lignin ratio should decrease. The cellulose/lignin ratios for both controls and LR sites decreased with age (Figure 2.2(b)). The rate of decline is 3% greater for LR sites than that of the control sites. After seven years the average cellulose/lignin ratio is 30% less for a LR site than a control site. A typical cellulose/lignin ratio for fresh MSW would be 2.0. Similar to volatile solids, the data suggests that most of the increased degradation occurred in the early stages of recirculation. However, the data is not conclusive due to the variability in cellulose/lignin ratios.

From Figure 2.2(c), the LR and control sites degraded cellulose at rates of 5.8 and 5.4 %/yr, respectively. Similar to the cellulose/lignin ratio, the LR sites decomposed cellulose 8% faster than the control sites.

BMP: The most dramatic rate enhancement is seen for the BMP data. Data obtained from the Riverbend landfill suggests that BMP degrades by first-order kinetics. Based on first-order regression analysis, LR and control sites have rate constants of 0.4329 and 0.1922 yr^{-1}, respectively (Figure 2.2(d)). This is an improvement of 125% from recirculating leachate. Since the generation rate of methane is an important consideration for gas collection efficiency and reduction in the discharge of greenhouse gases to the environment, the increased rate of BMP destruction is an important advantage for LR landfills.

Correlations: Volatile solids, cellulose, and BMP all show the biodegradation that is occurring. Parameters acted on by the same processes should correlate with one another. Figure 2.3 shows the correlation between cellulose and volatile solids. The parameters are even more correlated for the LR data than for the control data.

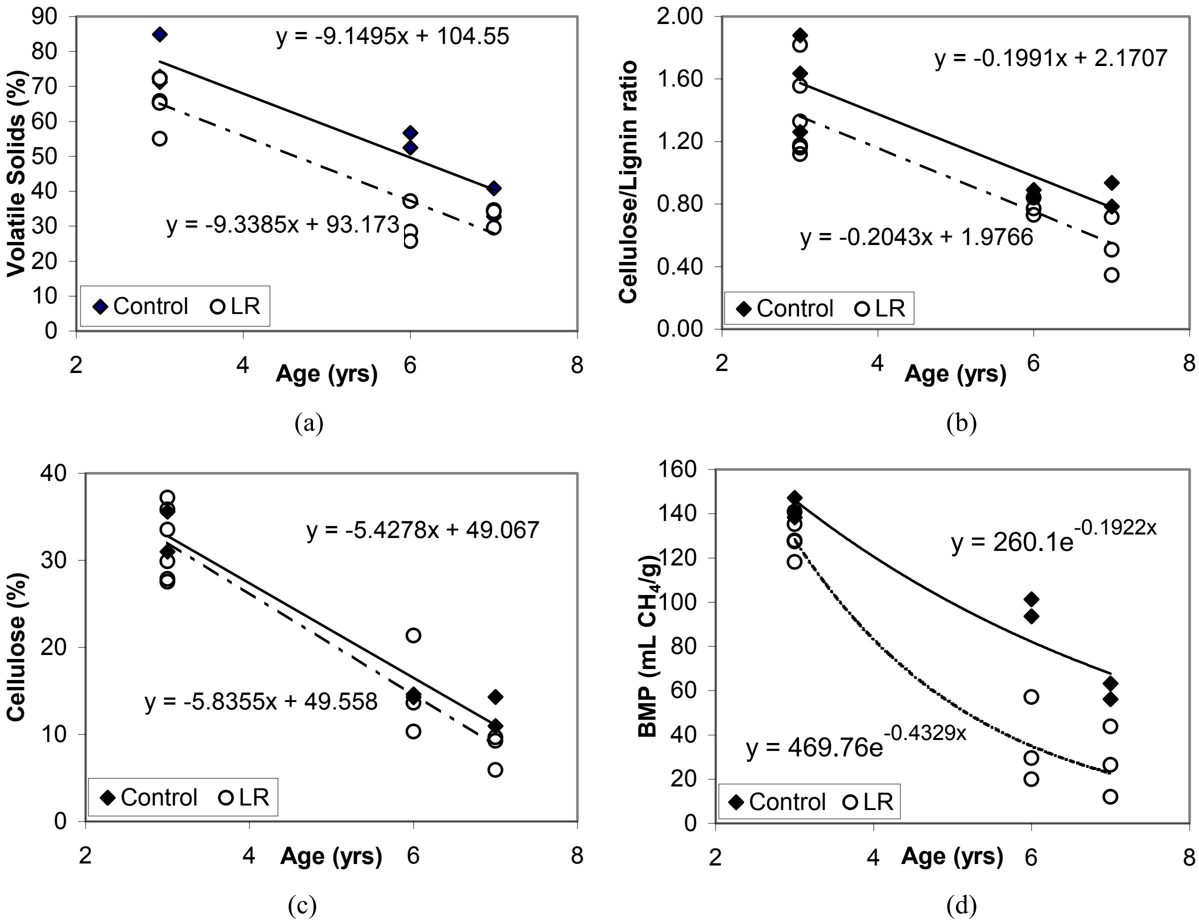


FIGURE 2.2 – (a)VOLATILE SOLIDS, (b)CELLULOSE/LIGNIN RATIO, (c)CELLULOSE, AND (d)BMP VERSUS LF AGE FOR LR AND CONTROL SITES

This is due to the enhanced degradation that is occurring in the LR cells. Since these parameters are all decreased by degradation, then the more dgradation that occurs the more related these parameters become. From the R^2 values in Table 2.1, it can be concluded that all three of these parameters are interrelated (moreso for the LR sites). Therefore, volatile solids alone may be used to monitor the degradation occurring in a landfill. This reduces the lab work and costs required to monitor stabilization.

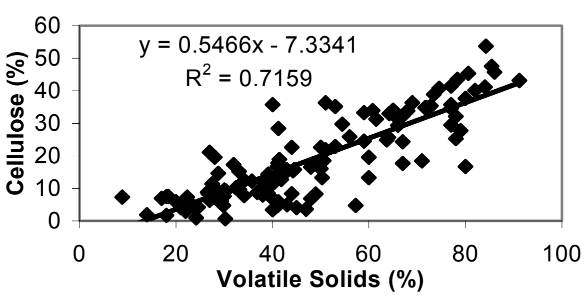


FIGURE 2.3 – LINEAR CORRELATION BETWEEN VOLATILE SOLIDS AND CELLULOSE

TABLE 2.1 – R^2 VALUES FOR CORRELATED PARAMETERS

Correlation	Mixed	Control	LR
VS-Cellulose	0.7159	0.7360	0.7534
BMP-Cellulose	0.6530	0.5131	0.6854
BMP-C/L ratio	0.4970	0.3257	0.5618
VS-C/L ratio	0.4274	0.3307	0.4826
BMP-VS	0.6469	0.6762	0.6821

Density: A major benefit of increased degradation is settlement and volume recovery. Dry density is one way to universally compare the volume that can be recovered from settlement. Figure 2.4 shows the average rate of compaction is 263-lbs/cu yd/yr and 170-lbs/cu yd/yr for LR and control sites, respectively. This translates to 55% more settlement for LR sites than control sites.

There are two mechanisms by which increased moisture content causes increased density. First, wet refuse will physically compact more than dry refuse. Second, biodegradation, through hydrolysis and metabolism, decreases the particle size of the refuse. Smaller particles compact more densely.

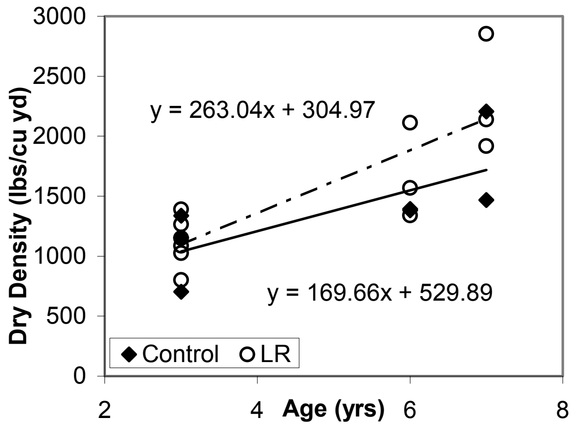


FIGURE 2.4 – DRY DENSITY OF LR AND CONTROL SITES OF VARIOUS AGES

Temperature: As microbes degrade MSW they give off heat. Therefore, an increase in degradation rate will also increase the rate that heat is generated. Thus, higher temperatures indicate enhanced biodegradation. In all cases, the leachate recirculation areas had higher maximum temperatures. Figure 2.5 shows the typical temperature profile for both control and LR sites. The LR cell at Atlantic reaches its maximum temperature about 35 feet below ground surface (ft bgs) and is isothermal below this point. This trend implies that the degradation rate is at a maximum below 35 ft bgs.

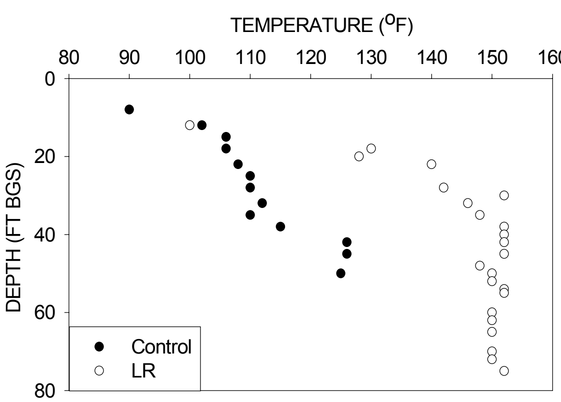


FIGURE 2.5 – TEMPERATURE WITH DEPTH AT ATLANTIC LANDFILL

SUMMARY

Analytical results from field data collected to date indicate that leachate recirculation does increase degradation. The degradation rate for volatile solids, cellulose/lignin ratio, and cellulose all increased by less than 10% for leachate recirculation landfills versus the controls. The first-order rate constant describing the decline in BMP was 125% higher for LR landfills. The dry densities of in-place refuse increased by 55% for landfills recirculating leachate. Therefore, leachate recirculation landfills should recover volume 1.5 times faster than control landfills. The increased rate of stabilization decreases the time that the landfill poses a risk to the environment. The extent of the increased biodegradaton is relative to the increase in moisture content. The average increase in moisture content was small (<5%). Therefore, the rate increases were also relatively small.

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Chapter 3

THE USE OF BIOCHEMICAL AND PHYSICAL DATA TO ESTIMATE THE STABILITY OF A BIOREACTOR LANDFILL IMPACT OF LANDFILL BIOREACTORS

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ABSTRACT

The objective of this paper is to evaluate the effectiveness of the bioreactor process and to optimize the operation of a bioreactor. Waste Management built a six acre bioreactor in Franklin, WI, which was sampled for one year. It contain a bioreactor side and a control side. The volatile solids, cellulose, and BMP degradation rates were increased by 56%, 87%, and 217%, respectively. Moisture content was the biggest factor influencing overall degradation.

The column study is designed to optimize three parameters under the control of an operator: moisture content, initial aeration period, and biosolids addition. The optimum moisture content is above 45%, but it is not safe to operate heavy equipment on refuse with greater than 45% moisture. Initial aeration did not speed up the overall degradation, but it did shorten the acidogenic phase. Finally, biosolids addition did not have a significant effect on degradation rates.

INTRODUCTION

Today, landfilling is the most widely used method of disposal for Municipal Solid Waste (MSW). Sanitary landfills are designed to minimize the risk of health or ecological damage from the disposal of solid waste. The concept of a sanitary landfill came about because of the problems associated with open dumps: fires, rodents, flies, odors, leachate, and explosive gas. Daily cover and compaction were used to reduce the risk of most of these problems, except for explosive gas and leachate generation. However, under subtitle D of the Resource Conservation and Recovery Act (RCRA) of 1976, strict regulations were enacted to deal with leachate and gas production.

Christensen and Kjeldsen (1989) claim that microbial activity will dominate the stabilization of the waste and hence govern the generation of landfill gas and the composition of leachate. Leachate is produced when water is allowed to contact the waste in a landfill, and can contain high levels of suspended solids and chemical oxygen demand. The strength of the leachate depends on the microbial activity within the landfill. Sanitary landfills reduce the volume of leachate by not allowing water to infiltrate into the landfill. Furthermore, all leachate generated is collected and treated *ex-situ*.

However, reducing the moisture in a landfill extends the time frame of stabilization, often for decades. There is a risk of groundwater pollution from leachate as long as there is degradable material within the landfill. Therefore, by limiting the moisture in a landfill the time that a landfill poses a risk of groundwater contamination is extended. Another benefit of rapid stabilization is that the liners are more likely to be in tact, while the leachate strength is high. In sanitary landfills, leachate strength can be high for decades after closure, giving liners more time to fail.

Bioreactor landfills require close monitoring and control of conditions within the landfill. Unlike sanitary landfills, bioreactor landfills have many parameters that the operator can adjust in order to increase stabilization and gas production. Some of these parameters are moisture content, frequency of recirculation, waste placement, temperature, addition of nutrients, microbial inoculation, aeration, and addition of buffers. Proper management of these and other parameters should lead to very quick stabilization of waste and high methane production rates.

The redox potential within a landfill provides an indicator of the mechanism of waste degradation. Generally, a high redox potential (aerobic conditions) causes accelerated degradation of waste, but air must be supplied which increases operational costs. Furthermore, aerobic degradation has a potential to produce fires because of the excess heat and oxygen.

Several researchers have recently suggested a two-stage process, which consists of an aerobic and anaerobic phase. Aerobic conditions in the first stage would be maintained by supplying air to the landfill. The aerobic microorganisms in the landfill would first quickly metabolize the readily degradable organics. Once the readily degradable material has been metabolized, the air supply would be shut off and anaerobic conditions would become established. The more resistant material would be slowly degraded by anaerobic mechanisms.

This two-stage process would combine the advantages of both aerobic and anaerobic mechanisms, while eliminating some of the disadvantages. The overall stabilization rate is increased, while shortening the acidogenic phase, which increases methane production. Another benefit is that anaerobic pathways that can degrade resistant chemicals such as PAHs are still possible. Although more research is necessary, this process appears to be the most efficient use of redox potential to accelerate degradation.

Addition of moisture enhances methanogenesis, nutrient transport, pH buffering, and microbial degradation. Lysimeter studies of the effect of moisture content on waste degradation recommend a minimum of 25 percent (wet basis) and 40 to 70 percent for optimum degradation. However, operating landfills greater than 35 percent moisture content can cause problems with equipment moving over the refuse (Gurijala, 1993).

Adding biosolids from a wastewater treatment plant is the most common method of microbial inoculation. Results from studies evaluating the effects of such additions have been inconsistent. Reinhardt and Townsend (1998) claim that any effect may be due to moisture addition or buffering more than seeding. Due to the varying effects and difficulty of handling, biosolids are not commonly added.

McBean et al. (1995) stated that the intent of a monitoring program is to determine the degree to which a landfill and any associated containment system are functioning in accord with the design objectives. Monitoring is especially important for bioreactor landfills because of the added process control and lack of experience in their operation. One of the major savings with a bioreactor will be that once guidelines are established, the time that is required for monitoring will be shortened. If it is shown that the landfill is stable after fifteen years, as opposed to thirty to fifty years, then monitoring can be stopped and the land can be used for alternative purposes.

This paper is divided into two sections: a column study and a pilot bioreator study. The data presented in this paper is from analyses performed on MSW.

METHODS

The bioreactor was sampled using a drill rig outfitted with a 36-inch bucket auger to collect refuse. Samples were collected from three heights throughout a ten-foot section and shipped to Virginia Tech in coolers. For the columns, samples were taken from four heights along each column using a 1¼” auger bit with a two-foot extension. Samples from the four heights were composited to make one sample per column for each sampling period.

MSW wet density was measured in the field by placing each ten-foot segment into a tared roll-off box and weighing it. The volume of a ten-foot high, three-foot diameter cylinder (2.62 yd^3) was divided into the weight to calculate the wet density. The dry density was calculated using the wet density and the measured moisture content. Wet and dry densities are reported in units of pounds per cubic yard (lbs/yd^3).

The moisture content was measured by weighing out between 500 and 1000 grams of wet, unshredded MSW (standard method 2540-B) in an aluminum pan and drying at 105°C until a constant weight (usually < 2 days) (APHA et al., 1995). The weight lost during drying is divided by the original sample weight. Moisture content is reported as a percent by weight.

The pH was obtained by mixing 50% by weight wet, unshielded MSW and distilled water in a one-liter glass beaker. The mixture was allowed to come to equilibrium at 20°C (approximately 5 hours). Finally, a calibrated pH electrode was placed into the liquid until a stable reading could be obtained.

Shredding was accomplished in two stages. First, dry samples were milled in a store bought blender. Second, the samples were put through a Thomas Intermediate Wiley Mill with a 10-mesh screen. Nongrindables, such as rocks, nails, etc., were also weighed.

Standard method 2540-E was used to measure volatile solids (APHA et al., 1995). Volatile solids consist of the weight lost during combustion of one- to two-grams of dry, milled MSW in a muffle furnace at 550°C until a constant weight is achieved. The units of volatile solids are percent by weight.

The cellulose and lignin analysis was taken from ASTM E 1758-95^{e1} (1995). A sample size of 300 mg of dry, shredded MSW was used for this measurement. The cellulose was hydrolyzed into its glucose monomers in two stages using sulfuric acid. First, the samples were digested in three milliliters of 72% sulfuric acid in a water bath at 45°C for two hours. Second, the samples were transferred to 250 mL septa bottles using 84 mL of nanopure water and autoclaved for one hour at 121°C and 15 psi. Next, they were filtered using standard TSS filters. The volatile suspended solids (combusted at 550 °C) remaining after hydrolysis was considered lignin. The filtrate was then neutralized using $CaCO_3$ powder directly. The glucose was quantified using HPLC with a refractive index detector and HPX-87C carbohydrate column.

Biochemical methane potential (BMP) was modified from a procedure developed by Dr. Barlaz (Barlaz, 2000). A sample size of 2.00 g of dry, milled MSW was added to a 250 mL Boston round septa bottle. Then, 100 mL of revised anaerobic mineral media (RAMM) was added to each bottle. The media was made following Dr. Barlaz's ingredients except for two important modifications. First, anaerobically digested biosolids were added at 10% by volume as an inocullum (Stinson and Ham, 1995). Second, the vitamin solution was modified according to Owen (1979). Table 3.1 shows the ingredients for the combined trace metals and vitamin solution.

TABLE 3.1 – STOCK SOLUTION FOR PREPARATION OF RAMM

Compound	**Concentration (g/L)**
Trace Metals	
$MnCl_2 * 2 H_2O$	20
$CoCl_2 * 6 H_2O$	30
H_3BO_3	5.7
$CuCl_2 * 2 H_2O$	2.7
$Na_2MoO_4 * 2H_2O$	2.55
$ZnCl_2$	2.1
Vitamins	
Biotin	0.02
Folic Acid	0.02
Pyridoxine hydrochloride	0.1
Riboflavin	0.05
Thiamin	0.05
Nicotinic acid	0.05
Pantothenic acid	0.05
B_{12}	0.001
p-aminobenzoic acid	0.05
Thioctic acid	0.05

The bottles were incubated inverted at 35°C for 45 days. At the end of the incubation period, excess pressure was relieved by connecting 1 L Teflon gas sampling bags to each bottle for twenty minutes while agitating the bottle. A 100-microliter sample was taken from the gas-sampling bag and injected into a GC with a carbosieve packed column and a flame ionization detector (FID). The volume of gas in the gas-sampling bag was measured using a 60 mL plastic syringe. This test was run in triplicate with one blank for every six bottles. The amount of methane measured in the blanks was deducted from that of the samples. The BMP is reported in units of milliliters of methane per gram of dry MSW at STP (mL CH_4/g).

COLUMN STUDY

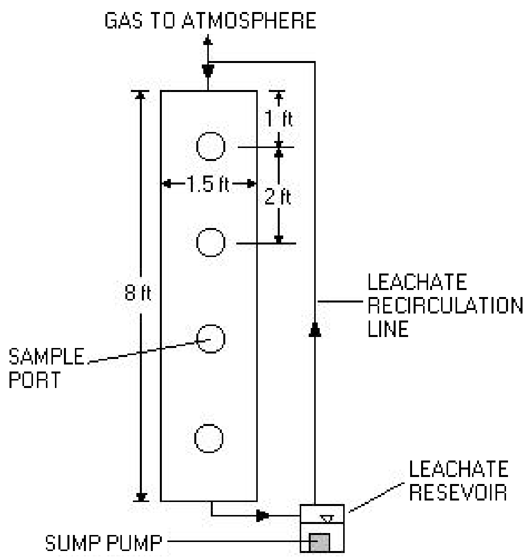

FIGURE 3.1 – DRAWING OF COLUMN

<u>Background</u>

The column study is designed to optimize conditions in a bioreactor. The three parameters being investigated are as follows: initial aeration period, moisture content, and anaerobic biosolids addition. Table 3.2 lists the conditions of the twelve columns used to investigate three moisture contents (25, 35, and 45% by weight), three initial aeration periods (0, 4, and 8 weeks), and biosolids addition (0 or 4 L). The column designated to have 35% moisture and 4 weeks aeration could not be analyzed because it was packed with mostly wood and was not consistent with the other columns. The columns were packed with MSW from incoming trucks at the Metro landfill (bioreactor for this project). The refuse was shredded with a chipper/shredder on-site then riffled before packing the columns. The columns are 18 inches in diameter, 8 feet tall, and made from one-inch thick HDPE. They are equipped with four sampling ports at heights of 1, 3, 5, and 7 feet. Five-gallon, sealable pails were used as leachate reservoirs. A one-quarter horsepower submersible pump with floating switch was placed into the reservoir to recirculate leachate back to the top of the column. Four liters of biosolids were added to the reservoir of each column that received such an addition. A one-third horsepower aerator was connected to four columns in parallel using ¾ inch flexible tubing. The columns were aerated for ten hours each day during their aeration period.

Due to increased risk of fire, temperature probes were installed at a height of four feet. However, the temperatures of the columns were only slightly above room temperature. The latest work with these columns involves running hot water around the columns and insulation in order to jump-start the autothermal process. The results included in this paper are for data collected before external heating was initiated.

TABLE 3.2 – CONDITIONS OF COLUMNS

Column	Aeration (Weeks)	Moisture (%)	Biosolids Addition
1	0	45	No
2	8	35	No
3	8	45	No
4	8	45	Yes
6	4	45	No
7	4	25	No
8	4	45	Yes
9	8	25	No
10	0	35	No
11	0	45	Yes
12	0	25	No

<u>Results</u>

<u>Moisture Content:</u> The average moisture contents measured for the three sets of columns were 25%, 39%, and 45%. After some initial adjustments between the first and second sampling periods the moisture contents remained relatively constant (Figure 3.2). All of the 45% moisture columns are still producing leachate, while those designed to be at 35% have absorbed all of the water added. Thus the elevated moisture contents of the two 35% moisture columns cannot be corrected.

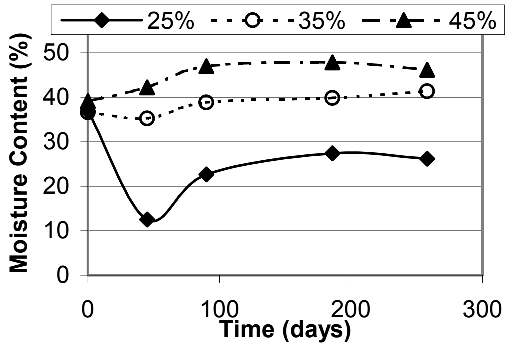

FIGURE 3.2 - AVERAGE MOISTURE CONTENTS OVER TIME

During sampling, I noted that the liquid seemed to be localized in certain areas around the outsides of the 35% moisture columns. This poor distribution of water has its biggest effect on the BMP results.

Volatile Solids: The effect of moisture content on volatile solids is shown in Figure 3.3. The columns at 45% moisture show a 78% increase in the degradation rate of volatile solids (0.0308 %VS/day) relative to the 25% columns (0.0173 %VS/day). Similarly, those at 35% are degrading 54% faster (0.0267 %VS/day). Therefore, adding moisture beyond 35% does increase degradation.

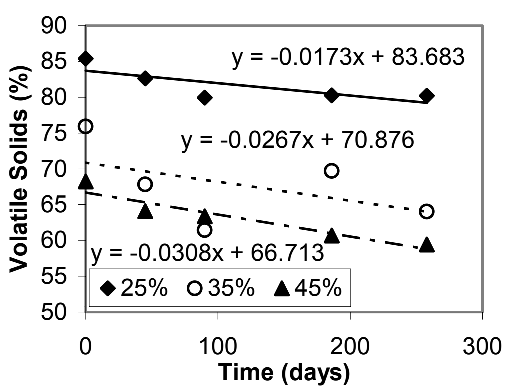

FIGURE 3.3 - EFFECT OF MOISTURE ON VOLATILE SOLIDS

Aeration did not have a consistent effect on the degradation of volatile solids. Four weeks aeration had the highest rate of degradation, but eight weeks aeration had the lowest volatile solids (Figure 3.4).

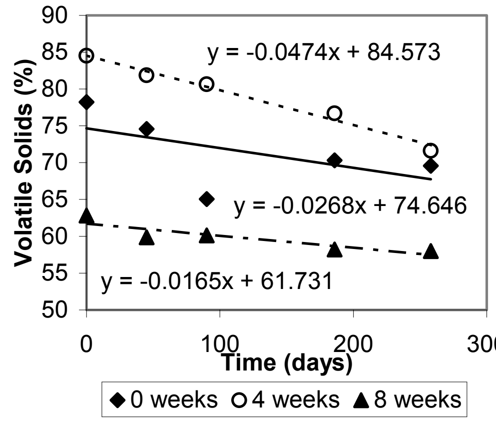

FIGURE 3.4 – EFFECT OF AERATION ON VOLATILE SOLIDS

The addition of biosolids also did not show an effect on volatile solids degradation. The control columns degraded at a slightly slower rate, but they also began at lower initial VS values (Figure 3.5).

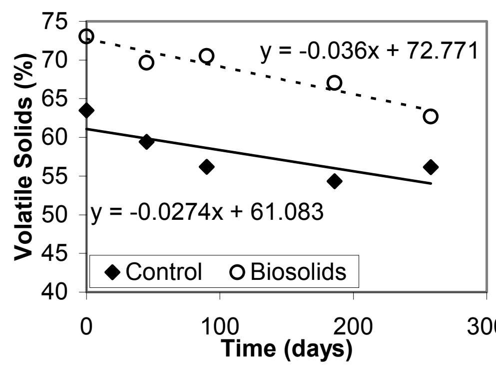

FIGURE 3.5 – EFFECT OF BIOSOLIDS ADDITION ON VOLATILE SOLIDS

Cellulose/Lignin: Cellulose/lignin ratios were the most variable of all the parameters measured. Since these columns have been sampled for less than one year the degradation enhancement is relatively small compared to this variability. Furthermore, lignin is relatively recalcitrant, thus it stays fairly constant. Therefore, cellulose alone is more indicative of the degradation that is occurring in the columns. From Figure 3.6, it can be seen that cellulose in the 25% and 35% moisture columns remained relatively constant, while that of the 45% moisture columns decreased significantly. After less than one year, the columns with 35% moisture have 26% less cellulose than those with 25% moisture, while the 45% moisture columns have 37% less cellulose. Once again moisture content has a dramatic effect on degradation.

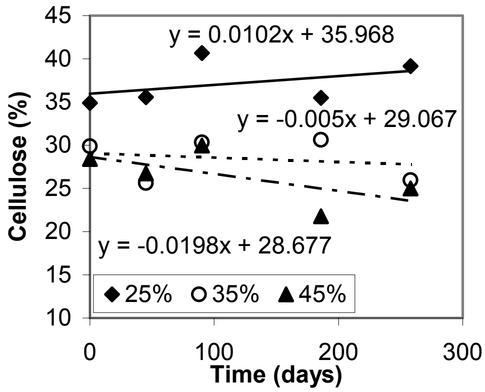

FIGURE 3.6 – EFFECT OF MOISTURE CONTENT ON CELLULOSE

The initial aeration period seemed to have less of an effect on the cellulose degradation than moisture content. The rates increase very slightly with increased initial aeration time (Figure 3.7). In February, the columns with eight weeks aeration had 34% less cellulose than the controls.

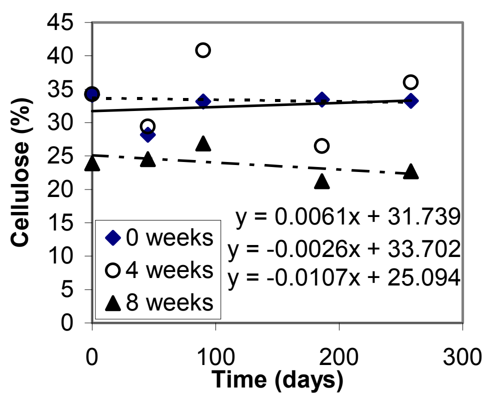

FIGURE 3.7 – EFFECT OF AERATION ON CELLULOSE

From Figure 3.8, the addition of biosolids actually reduced the cellulose degradation rate by 73%. The biosolids that were added accumulated at the top of these columns. Excessive fungal growth was observed around the sampling ports also. This excess growth may have clogged pores and restricted even distribution of moisture.

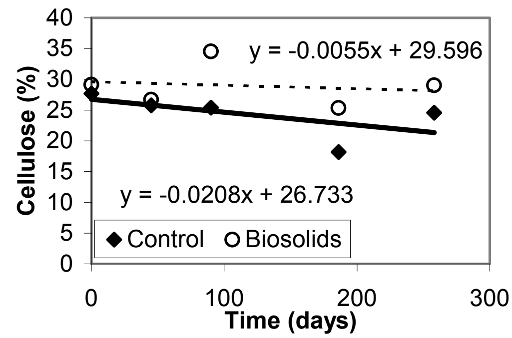

FIGURE 3.8 – EFFECT OF BIOSOLIDS ON CELLULOSE

<u>BMP:</u> The results from the BMP analyses give us the most insight into the biodegradation process. It has been well documented that increasing moisture will increase biodegradation. However, the BMPs for the 35% moisture columns do not show enhanced degradation (Figure 3.9). Because the 35% columns are not producing leachate, the leachate is not recirculated. As shown in chapter 2, recirculation of leachate greatly increases methane production. The rate of decline in BMP for the 45% columns is 84% greater than that of the 25% columns.

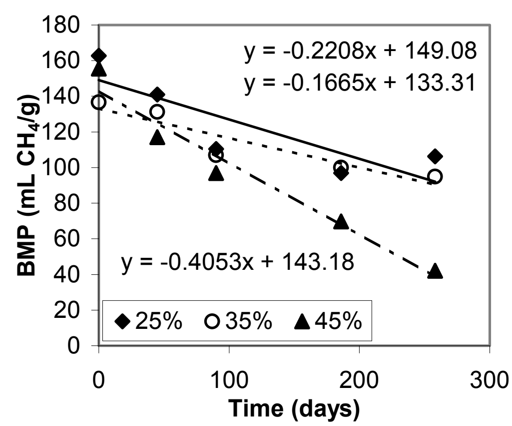

FIGURE 3.9 – EFFECT OF MOISTURE CONTENT ON BMP

Initial aeration was expected to increase consumption of readily degradable organic matter, such as food waste. For the aerated columns, the BMP dropped quickly in the beginning and then more slowly after aeration is ceased. There is no significant difference between four and eight weeks aeration. This may be due to the temperaturesnot being elevated. The columns remained slightly above room temperature (~70°F).

The addition of biosolids did not increase the rate of decline in BMP (Figure 3.10). The average first-order rate constant was about 1.73 yr^{-1} for both controls and amended columns.

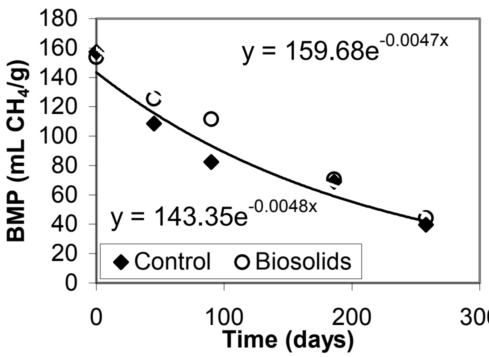

FIGURE 3.10 – EFFECT OF BIOSOLIDS ADDITION ON BMP

Column Summary

The data collected suggest that the moisture content optimum for degradation is above 45%, but according to Gurijala it is not safe to operate heavy equipment on refuse with greater than 35% moisture (1993). Thus, optimum moisture content for a bioreactor may be dependent on shear strength rather than the increase in degradation. Initial aeration did not speed up the overall degradation, therefore the optimum amount of aeration could not be determined from the data. Finally, biosolids did not have a significant effect on degradation rates. However, millions of gallons are required to increase the moisture content of a full-scale landfill. Therefore, the revenue from disposing of biosolids is justification enough for the addition of biosolids.

PILOT BIOREACTOR

Background

The Metro Landfill in Franklin, WI began receiving refuse in November 1999 and was filled to capacity by February 2000. The single cell landfill is approximately three acres and contains a control and a bioreactor side. The MSW coming into the bioreactor side was mixed with water and liquid wastes. Furthermore, each lift was aerated using the leachate collection pipes until the next lift was added (2-4 weeks). Vertical gas collection wells were built to collect the excess methane produced. Leachate was recirculated to infiltration trenches just below the cap. Liquid biosolids from the anaerobic digestors at the local wastewater treatment plant (WWTP) were added as as source of nutrients, but mainly as an inoculum of anaerobes. The biosolids were mixed before the refuse was compacted.

Results

Sample averages were used in order to give one data point per side for each sampling period. In February, for example, the bioreactor was sampled at three locations and four depths per location. Therefore, for volatile solids, which are run in triplicate, the value used in the regression analysis is an average of 36 values. This stabilizes the heterogeneity of the individual samples.

Moisture Content and pH: The pH results were quite variable. The average pH for the control side was 6.34 (5.07-7.12), while the average pH for the bioreactor side was 6.47 (5.01-8.04). As you can see from Figure 3.11, the pH for the bioreactor began to increase several months before that of the control. Initial aeration allows the readily degradable organic matter to be consumed aerobically, thus shortening the acidogenic phase and making it less severe.

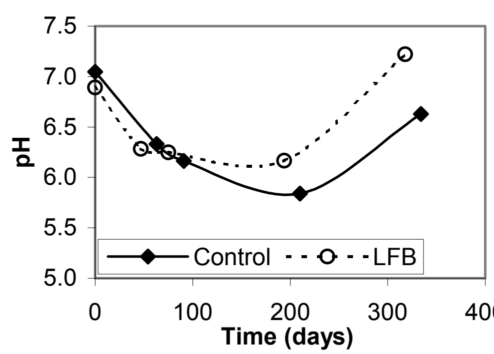

FIGURE 3.11 – pH OF BIOREACTOR AND CONTROL SITES

The moisture content of both sides remained fairly constant throughout the sampling period, with the average moisture contents being 27% and 34% for the control and bioreactor, respectively. Moisture content is the most influential factor enhancing biodegradation. Therefore, the disparities between the control and bioreactor could be expanded if the difference in moisture content was greater than 7%.

Volatile Solids: Degradation of volatile solids occurred at rates of 0.0936 and 0.06 (%VS/day) for the bioreactor and control, respectively. Therefore, the bioreactor is losing volatile solids 56% faster than the control.

Cellulose/Lignin: The cellulose data is extremely insightful. The bioreactor showed an 87% increase in the degradation rate of cellulose versus the control (0.0518 and 0.0277 %cellulose/day). Similarly, the cellulose/lignin ratio results show a 71% increase in the degradation rate (Figure 3.12).

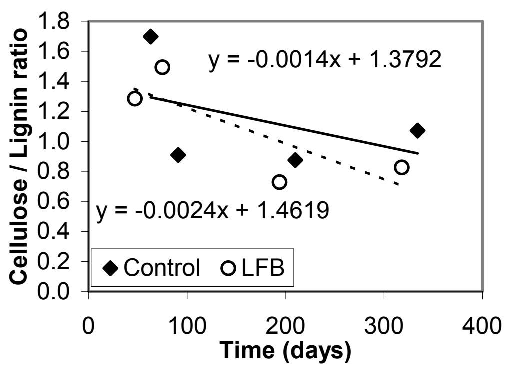

FIGURE 3.12 – CELLULOSE/LIGNIN RATIO OVER TIME

BMP: Perhaps the most pronounced effect of the bioreactor process is observed in the BMP data. The first-order rate constant is increased 271%, from 0.0007 to 0.0026 d^{-1} (Figure 3.13).

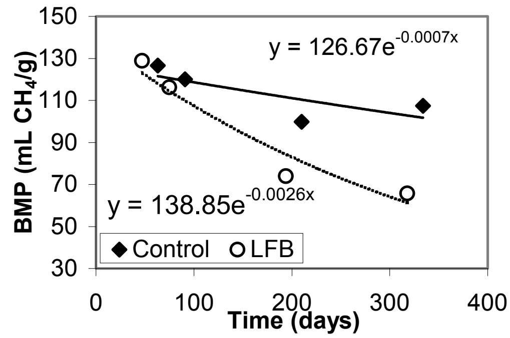

FIGURE 3.13 – BMP FOR THE CONTROL AND BIOREACTOR OVER TIME

Correlations: Volatile solids, cellulose, cellulose/lignin ratio, and BMP are all paramters that assess the stability of MSW. Correlations between these parameters have been shown to exist for leachate recirculation landfills (Chapter 2). It was also shown that when degradation is enhanced the parameters are more closely related. Figure 3.14, shows the correlation between cellulose and volatile solids for all the data collected from the Metro landfill.

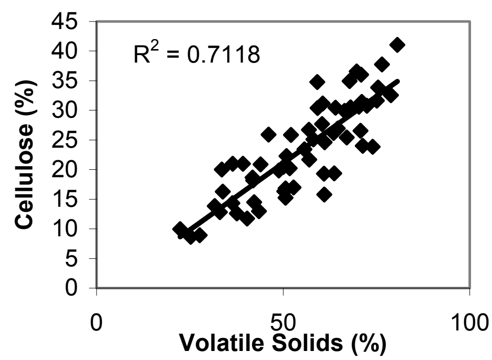

FIGURE 3.14 - CORRELATION BETWEEN CELLULOSE AND VOLATILE SOLIDS

The correlation between parameters is greater for the bioreactor data than for the control data (Figure 3.15). Y1 is the regression equation for the control data, while y2 is that of the LR data. This confirms the trend established in Chapter 2. Table 3.3 shows the change in R^2 value for the control and bioreactor.

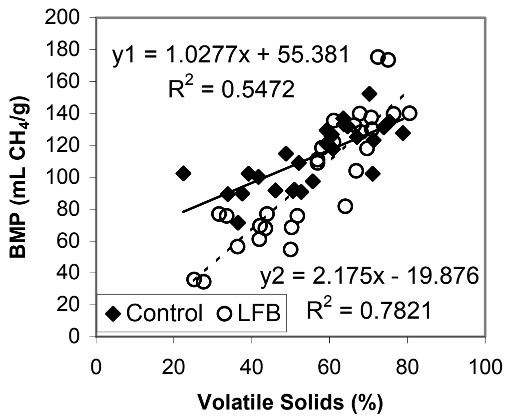

FIGURE 3.15 - CORRELATION BETWEEN BMP AND VOLATILE SOLIDS FOR BIOREACTOR AND CONTROL

TABLE 3.3 – R^2 VALUES FOR BIOREACTOR AND CONTROL

Correlation	Mixed	Control	Bioreactor
VS-Cellulose	0.7118	0.5488	0.8228
BMP-VS	0.3785	0.5472	0.7821
BMP-Cellulose	0.2048	0.3434	0.6266
BMP-C/L ratio	0.0922	0.0942	0.4568
VS-C/L ratio	0.1391	0.0834	0.5152

Summary of Bioreactor Results

For all parameters measured, the bioreactor showed enhanced degradation rates. The volatile solids, cellulose, and BMP degradation rates were increased by 56%, 87%, and 271%, respectively. Moisture content was the biggest factor influencing overall degradation.

The large decrease in BMP suggests that methane production was also enhanced. Furthermore, methane is more effeciently recovered when production rates are high, thus decreasing the release of a greenhouse gas. The pH data shows the bioreactor transitioning out of the acidogenic phase much sooner than the control. This would also enhance methane production.

The improved correlation of Volatile Solids, Cellulose, and BMP for the bioreactor suggest that monitoring only one of these may be sufficient to assess the stability of a bioreactor. This would significantly reduce lab costs. If BMP did not have to be tested, then the turn-around time for data would be reduced tremendously. Thereby, giving the controller more time to adjust parameters to maximize degradation.

CONCLUSION

In conclusion, the bioreactor process is an effective alternative to sanitary landfills. The increased degradation shortens the time that the landfill poses a risk to the groundwater and atmosphere. Furthermore, with increased methane production, bioreactors enable more efficient methane recovery. Through leachate recirculation, the leachate is treated and the total volume is reduced. Finally, increased degradation enables increased volume recovery.

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APPENDIX

TABLE 1A – DATA FROM ANALYSES ON MSW FROM THE ATLANTIC LANDFILL IN WAVERLY, VIRGINIA

Sample Date	Location	Depth	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig	pH	Wet Density (lbs/cuyd)	Dry Density (lbs/cuyd)	BMP (mL/g)
Control	3-1	10-20	41	69	36	22	1.62	6.15	1872	1104	166
Control	3-1	20-30	39	86	46	27	1.69	5.74	1367	834	174
Control	3-1	30-40	31	50	23	16	1.44	5.71	2720	1877	115
Control	3-1	40-50	35	80	38	21	1.80	6.32	2368	1539	134
Control	3-2	10-20	46	82	40	20	2.04	6.30	1459	788	128
Control	3-2	20-30	31	60	13	33	0.40	6.39	1215	838	182
Control	3-2	30-40	64	77	36	32	1.14	6.87	1849	666	120
Control	3-2	40-50	64	72	35	24	1.48	7.11	1436	517	133
LR	2-1	10-20	70	59	33	22	1.55	7.39	3086	926	65
LR	2-1	20-25	70	51	22	27	0.81	7.51	2261	678	61
LR	2-2	10-20	41	53	23	22	1.04	6.58	2574	1519	73
LR	2-2	20-30	49	67	24	26	0.95	6.73	2139	1091	161
LR	2-2	30-40	60	78	32	23	1.38	6.81	2093	837	138
LR	2-2	40-50	57	77	35	30	1.16	6.94	1558	670	141
LR	2-2	50-60	60	56	26	22	1.17	7.17	2628	1051	101
LR	2-2	60-70	65	64	26	27	0.97	7.41	2697	944	115
LR	2-2	70-75	64	66	29	25	1.18	7.56	2964	1067	163
LR	2-3	10-20	49	51	36	27	1.34	7.21	1704	869	166
LR	2-3	20-30	47	53	35	23	1.52	6.52	2254	1195	196
LR	2-3	30-40	32	67	18	26	0.69	7.31	1864	1268	113
LR	2-3	40-50	47	78	25	25	1.01	11.51	2231	1182	115
LR	2-3	50-60	54	77	30	24	1.24	6.93	2063	949	104
LR	2-3	60-70	55	65	34	26	1.31	6.28	2353	1059	152
LR	2-3	70-76	62	66	31	30	1.04	6.63			141
LR	2-4	10-20	41	67	32	26	1.27	6.71	1971	1163	131
LR	2-4	20-30	40	77	41	25	1.68	5.54	1986	1192	163
LR	2-4	30-40	44	84	41	25	1.63	5.65	1787	1001	144
LR	2-4	40-50	38	79	28	27	1.04	6.13	2101	1303	119
LR	2-4	50-60	43	68	34	24	1.41	6.81	2238	1276	137
LR	2-4	60-70	53	59	25	26	0.96	7.06	2055	966	118

TABLE 2A – DATA FROM ANALYSES ON MSW FROM THE CENTRAL LANDFILL IN POMPANO BEACH, FLORIDA

Sample Date	Location	Depth	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig	pH	BMP (mL/g)
05/21/00	Boring 7	40-50	28	27	11	11	1.07	8.26	16
		50-60	30	36	12	13	0.92	8.15	31
		60-70	29	40	11	11	1.05	7.59	15
05/22/00	Boring 8	10-20	21	22	5	7	0.76	8.24	9
		20-30	25	28	7	13	0.54	8.07	31
		30-40	32	41	18	19	0.94	7.83	27
		40-50	28	18	8	9	0.81	8.95	14
		50-60	33	50	13	19	0.69	7.31	17
		60-70	37	30	8	12	0.65	7.74	19
		70-80	43	41	19	25	0.75	7.56	39
		80-90	37	42	15	18	0.83	6.83	41
		90-100	26	33	15	25	0.62	7.29	54
05/23/00	Boring 9	10-20	41	27	9	15	0.58	8.24	48
		20-30	41	28	10	15	0.69	7.56	15
		30-40	54	41	6	11	0.55	7.86	24
		40-50	36	34	8	13	0.60	7.92	12
		50-60	29	27	9	14	0.63	7.80	24
		60-70	34	29	7	9	0.78	7.82	26
		70-80	32	38	12	18	0.66	7.68	22
		80-90	36	25	4	16	0.26	7.67	17
		90-100	31	40	12	18	0.64	7.73	36

TABLE 3A – DATA FROM ANALYSES ON MSW FROM THE EVERGREEN LANDFILL IN NORTHWOOD, OHIO

Type	Location	Depth	Moisture (%)	VS (%)		Lignin (%)	Cell/Lig	pH	Wet Density (lbs/cu.yd.)	Dry Density (lbs/cu.yd.)	BMP (mL/g)
LR	EB-1	8-18	22	40	12	22	0.56	7.51	2703	1800	37
LR	EB-1	18-28	43	30	1	25	0.03	8.04	2703	1800	8
LR	EB-1	28-38	36	44	15	24	0.64	7.21	2703	1800	22
LR	EB-1	38-48	21	34	12	17	0.74	7.18	2703	1800	41
LR	EB-1	48-58	28	22	7	13	0.57	7.53	4818	3493	26
LR	EB-2	8-18	27	24	1	18	0.05	6.96	2930	1917	6
LR	EB-2	18-28	35	57	5	28	0.17	6.88	2930	1917	3
LR	EB-2	28-38	41	30	9	15	0.60	6.69	2930	1917	27
LR	EB-2	38-46	43	27	9	18	0.56	7.26	2930	1917	14
LR	EB-3	8-18	14	27	8	12	0.73	6.83	4048	2853	57
LR	EB-3	18-28	23	33	10	19	0.50	7.38	4048	2853	26
LR	EB-3	28-38	38	28	10	14	0.70	7.43	4048	2853	43
LR	EB-3	38-48	49	30	9	10	0.93	7.43	4048	2853	49
Control	EB-4	13-23	28	64	25	24	1.05	6.00	2483	1469	95
Control	EB-4	23-33	20	29	15	16	0.93	6.73	2483	1469	49
Control	EB-4	33-43	33	42	13	16	0.78	6.82	2483	1469	53
Control	EB-4	43-53	25	41	17	23	0.72	7.05	2483	1469	55
Control	EB-4	53-63	30	39	14	17	0.85	7.14	2483	1469	60
Control	EB-4	63-73	33	51	19	23	0.83	6.79	2483	1469	96
Control	EB-4	73-83	32	24	4	8	0.76	7.82	2483	1469	19
Control	EB-4	83-93	43	38	8	24	0.34	7.81	2483	1469	23
Control	EB-5	11-21	25	32	17	16	1.11	6.57	3020	2030	74
Control	EB-5	21-31	28	32	10	15	0.65	7.03	3020	2030	75
Control	EB-5	31-41	18	30	5	8	0.55	8.29	3020	2030	31
Control	EB-5	41-51	22	37	9	18	0.49	8.05	3020	2030	56
Control	EB-5	51-61	23	29	6	12	0.48	7.69	3542	2381	30
Control	EB-5	61-71	18	9	7	7	1.13	7.55	3542	2381	71
Control	EB-5	71-81	31	45	16	7	2.21	6.56	3542	2381	106
Control	EB-5	81-91	34	48	18	21	0.86	7.17	3542	2381	63

TABLE 4A – DATA FROM ANALYSES ON MSW FROM THE MIDDLE PENINSULA LANDFILL IN GLENNS, VIRGINIA

Sample Date	Location	Depth	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig	pH	Wet Density (lbs/cu.yd.)	Dry Density (lbs/cu.yd.)	BMP (mL/g)
12/13/99	LR 1	10-20	36	41	28	14	2.01	6.34	2284	1462	115.62
12/13/99	LR 1	20-30	40	73	35	25	1.43	6.75	2100	1260	137.85
12/13/99	LR 1	30-40	38	75	41	19	2.17	6.86	2040	1265	142.99
12/13/99	LR 1	40-50	44	81	45	25	1.84	7.40	1925	1078	125.79
12/13/99	LR 1	50-60	37	61	31	18	1.82	6.69	3102	1954	129.53
12/13/99	LR 1	60-70	38	61	34	21	1.63	6.58	2147	1331	115.78
12/15/99	LR 2	10-20	38	72	35	28	1.23	5.84	1956	1213	145.20
12/15/99	LR 2	20-30	38	73	39	20	1.95	6.62	2208	1369	153.04
12/15/99	LR 2	30-40	30	54	30	18	1.63	6.70	1933	1353	112.81
12/15/99	LR 2	40-50	38	64	33	23	1.41	6.81	2452	1520	110.62
12/15/99	LR 2	50-60	37	91	43	34	1.26	6.16	1551	977	83.24
12/15/99	LR 2	60-70	41	78	44	24	1.85	6.41	1963	1158	104.65
12/15/99	GW-5	10-20	40	85	48	22	2.14	6.32	1379	827	135.77
12/15/99	GW-6	10-20	29	84	54	15	3.63	6.41	2090	1484	140.93

TABLE 5A – DATA FROM ANALYSES ON MSW FROM THE RIVERBEND LANDFILL IN MCMINNVILLE, OREGON

Sample Date	Location	Depth	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig	pH	Wet Density (lbs/cu.yd.)	Dry Density (lbs/cu.yd.)	BMP (mL/g)
10/11/99	Bio-1	5-15	25	14	2	11	0.19	6.35	1795	1346.25	6.59
10/11/99	Bio-1	15-25	32	40	7	25	0.27	6.32	1642	1116.56	4.86
10/11/99	Bio-1	25-35	43	45	4	32	0.13	7.60	1658	945.06	0.47
10/11/99	Bio-1	35-45	43	43	5	32	0.16	8.59	1665	949.05	4.39
10/11/99	Bio-2	5-15	52	40	3	20	0.17	8.55	1360	652.8	9.43
10/11/99	Bio-2	15-25	66	42	14	16	0.88	6.86	3002	1020.68	12.19
10/11/99	Bio-2	25-35	41	21	4	10	0.40	7.51	2296	1354.64	31.01
10/12/99	Bio-2	35-45	52	18	2	7	0.24	7.35	2296	1102.08	2.97
10/12/99	Bio-2	45-48	71	22	3	10	0.31	7.23			24.79
10/12/99	Bio-3	5-15	61	48	17	14	1.19	5.82	1711	667.29	90.38
10/12/99	Bio-3	15-25	40	47	4	8	0.47	6.96	1581	948.6	25.47
10/12/99	Bio-3	25-35	53	48	7	14	0.48	6.61	1184	556.48	66.18
8/3/99	GW-43	55-67	42						2841	1647.78	
8/3/99	GW-45	23-38	48						2910	1513.2	

TABLE 6A – DATA FROM ANALYSES ON MSW FROM THE SPRUCE RIDGE LANDFILL IN GLENCOE, MINNESOTA

Sample Date	Location	Depth	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig	pH	Wet Density (lbs/cu.yd.)	Dry Density (lbs/cu.yd.)	BMP (mL/g)
11/18/99	LR 1	18-28	46	44	23	31	0.74	6.95	2154	1163	63
11/18/99	1	28-38	32	44	8	10	0.84	6.56	2536	1724	92
11/18/99	1	38-48	35	41	5	9	0.55	6.94	2582	1678	56
11/18/99	1	48-58	47	39	9	10	0.86	6.60	2972	1575	39
11/18/99	1	58-68	34	18	8	11	0.66	6.77	2590	1709	36
11/17/99	LR 3	18-28	30	28	8	11	0.73	6.95	2108	1476	16
11/17/99	3	28-38	41	27	21	21	1.03	7.10	2147	1267	18
11/17/99	3	38-48	45	28	20	23	0.86	7.14	2322	1277	28
11/17/99	3	48-51	24	20	6	13	0.47	7.70			18
11/16/99	LR 4	18-28	24	17	7	15	0.47	7.03	2972	2259	18
11/16/99	4	28-38	19	40	36	29	1.21	6.78	2429	1967	41
11/16/99	Cont A	18-28	28	43	16	18	0.88	6.23	1734	1248	60
11/17/99	A	28-38	31	60	20	19	1.05	6.60	2376	1639	128
11/17/99	A	38-48	31	80	17	18	0.91	6.74	1872	1292	141
11/17/99	A	48-54	14	27	6	9	0.72	7.26			45
11/17/99	Cont B	18-29	16	71	18	21	0.90	6.71	1556	1307	115
11/17/99	B	29-38	26	50	16	19	0.86	6.20	1859	1376	75
11/17/99	B	38-48	25	49	8	11	0.77	6.55	1956	1467	114

TABLE 7A – DATA FROM ANALYSES ON MSW FROM THE METRO BIOREACTOR IN FRANKLIN, WISCONSIN

Cell	Location	Depth	Sample Date	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig	pH	BMP ($mLCH_4/g$)
Control	1	B	17-Nov-99	25	71	24	26	0.95	6.95	123
Control	1	C	17-Nov-99	26	67	25	28	0.93	7.12	125
Control	1	D	17-Nov-99	21	74	24	20	1.18	7.07	131
Control	4	B	19-Jan-00	26	65	27	18	1.73	6.52	132
Control	4	C	19-Jan-00	30	61	31	21	1.46	6.32	127
Control	4	D	19-Jan-00	32	59	35	19	1.91	6.15	121
LFB	1	B	3-Dec-99	23	33	13	12	1.19	6.51	96
LFB	1	C	3-Dec-99	27	40	12	21	0.55	7.01	122
LFB	1	D	3-Dec-99	35	51	15	25	0.63	7.15	144
LFB	4	B	19-Jan-00	31	66	30	20	1.50	6.16	133
LFB	4	C	19-Jan-00	33	61	25	21	1.15	5.89	136
LFB	4	D	19-Jan-00	39	58	25	21	1.20	6.80	118
Control	0-15	A-B	16-Feb-00	33	59	30	25	1.25	7.05	129
Control	15-25	A-B	16-Feb-00	27	75	34	33	1.07	6.55	135
Control	25-35	A-B	16-Feb-00	26	64	19	36	0.54	5.44	133
Control	35-45	A-B	16-Feb-00	38	79	33	30	1.09	5.78	128
Control	0-13	C-D	16-Feb-00	26	70	31	30	1.02	6.21	152
Control	13-25	C-D	16-Feb-00	28	51	17	32	0.54	6.65	91
Control	25-36	C-D	16-Feb-00	24	34	16	23	0.69	6.71	89
Control	36-49	C-D	16-Feb-00	35	71	31	29	1.11	6.41	102
LFB	0-10	A-B	16-Feb-00	32	71	36	21	1.75	6.14	57
LFB	10-20	A-B	16-Feb-00	36	57	22	18	1.17	6.81	111
LFB	20-30	A-B	16-Feb-00	31	64	30	22	1.37	6.72	82
LFB	30-40	A-B	16-Feb-00	33	67	30	29	1.02	6.29	104
LFB	0-10	B-C	16-Feb-00	41	70	37	23	1.59	6.20	73
LFB	10-20	B-C	16-Feb-00	40	81	41	25	1.62	6.46	74
LFB	20-30	B-C	16-Feb-00	28	71	27	28	0.94	6.21	137
LFB	30-40	B-C	16-Feb-00	28	68	35	15	2.28	6.23	140
LFB	0-10	C-D	16-Feb-00	42	76	38	19	2.03	5.95	140
LFB	10-20	C-D	16-Feb-00	42	72	31	26	1.21	5.01	175

TABLE 7A (CONT) – DATA FROM ANALYSES ON MSW FROM THE METRO BIOREACTOR IN FRANKLIN, WISCONSIN

Cell	Location	Depth	Sample Date	Moisture (%)	VS (%)	Cellulose (%)	Lignin (%)	Cell/Lig	pH	BMP ($mLCH_4/g$)
LFB	20-30	C-D	16-Feb-00	41	75	32	20	1.58	6.48	174
LFB	30-40	C-D	16-Feb-00	34	68	31	22	1.39	6.49	128
LFB	0-10	C-D	14-Jun-00	35	52	20	7	0.35	6.10	76
LFB	10-20	C-D	14-Jun-00	36	44	21	16	0.75	5.97	77
LFB	20-30	C-D	14-Jun-00	30	44	13	10	0.75	6.09	68
LFB	30-40	C-D	14-Jun-00	59	61	16	14	0.89	6.16	122
LFB	0-10	B-C	14-Jun-00	23	28	9	7	0.82	6.41	35
LFB	10-20	B-C	14-Jun-00	31	32	14	12	0.85	5.94	77
LFB	20-30	B-C	14-Jun-00	33	42	18	15	0.83	6.10	61
LFB	30-40	B-C	14-Jun-00	29	34	20	12	0.60	6.55	76
Control	0-10	B-C	14-Jun-00	25	22	10	9	0.89	6.47	103
Control	10-20	B-C	14-Jun-00	27	38	13	9	0.72	5.75	90
Control	20-30	B-C	14-Jun-00	32	42	19	16	0.84	6.00	100
Control	30-40	B-C	14-Jun-00	32	46	26	16	0.63	5.49	92
Control	0-10	C-D	14-Jun-00	33	64	26	23	0.86	5.07	137
Control	10-20	C-D	14-Jun-00	23	37	21	14	0.68	6.02	71
Control	20-30	C-D	14-Jun-00	27	53	17	27	1.60	6.01	91
Control	30-40	C-D	14-Jun-00	24	49	20	16	0.80	5.92	115
LFB	A-B	0-20	16-Oct-00	23	25	9	9	0.96	6.90	36
LFB	A-B	21-33	16-Oct-00	36	42	15	19	0.77	6.83	69
LFB	A-B	33-43	16-Oct-00	32	50	20	22	0.91	7.32	55
LFB	C-D	0-20	16-Oct-00	37	36	14	26	0.58	8.04	57
LFB	C-D	20-30	16-Oct-00	26	50	16	22	0.75	7.11	68
LFB	C-D	30-40	16-Oct-00	36	57	27	27	1.00	7.12	109
Control	A-B	0-20	16-Oct-00	31	52	26	21	1.25	6.62	109
Control	A-B	20-35	16-Oct-00	32	60	28	20	1.41	6.64	126
Control	A-B	36-49	16-Oct-00	27	56	23	31	0.77	6.73	97
Control	C-D	0-20	16-Oct-00	24	51	22	19	1.19	6.39	92
Control	C-D	20-30	16-Oct-00	23	39	21	18	1.19	6.53	102
Control	C-D	30-40	16-Oct-00	23	61	19	31	0.62	6.86	118

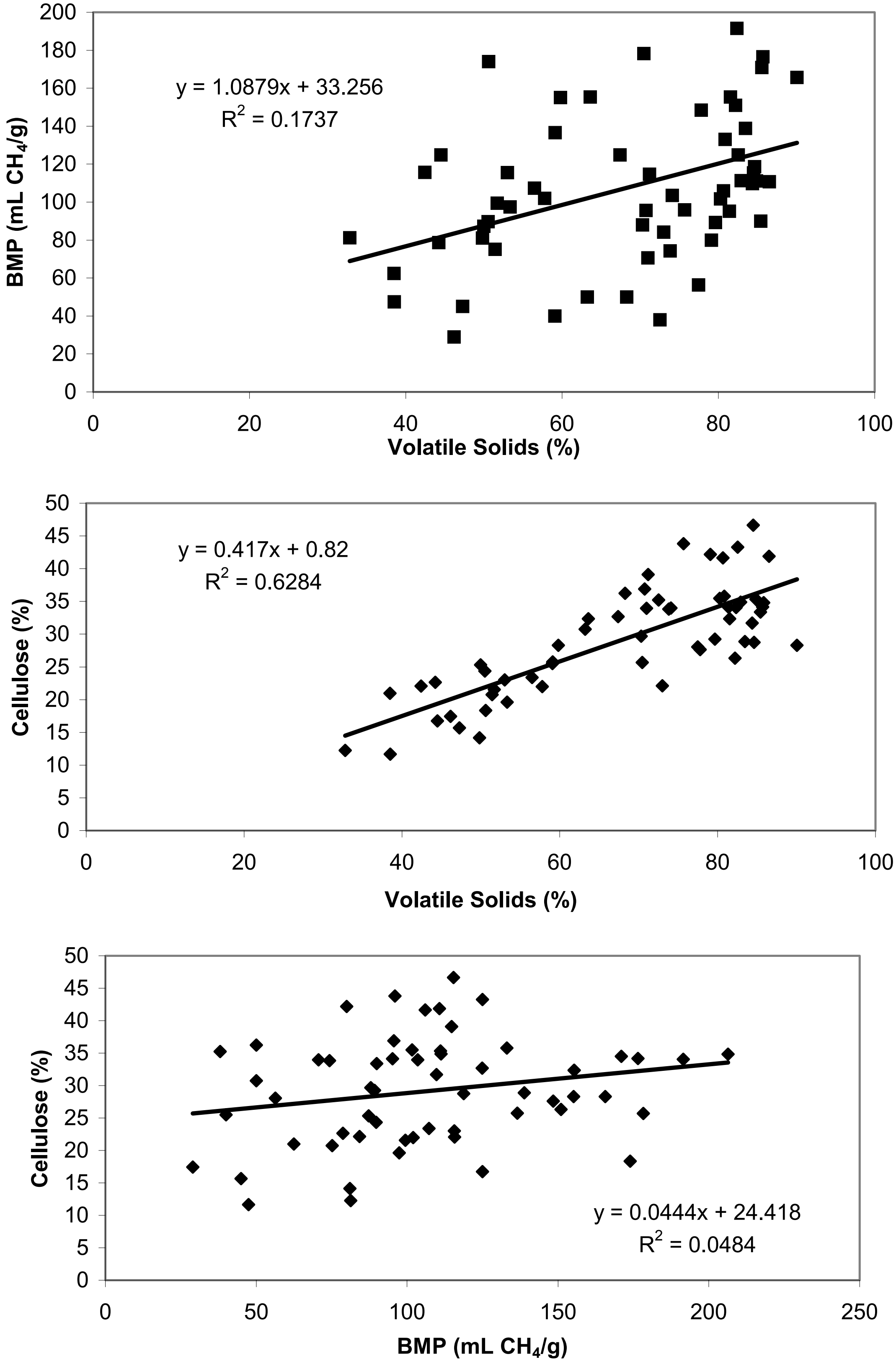


FIGURE 1A – CORRELATIONS BETWEEN COLUMN DATA

TABLE 8A – DATA FROM ANALYSES ON MSW FROM COLUMN STUDY

Column	Sample Date	Moisture (%)	VS (%)	Lignin (%)	Cellulose (%)	C/L	BMP (mL/g)
1	4/3/00	56	67	21	33	1.64	125
2	4/3/00	50	60	7	28	3.79	155
3	4/3/00	42	33	48	12	0.60	81
4	4/3/00	39	38	15	21	1.43	62
1	5/17/00	50	64	11	32	5.56	155
2	5/17/00	48	70	14	26	2.05	178
3	5/17/00	43	44	22	17	0.92	125
4	5/17/00	51	51	10	18	3.34	174
6	6/2/00	19	82	28	34	1.24	192
7	6/2/00	27	86	30	35	1.17	171
8	6/2/00	37	86	36	34	0.96	177
9	6/2/00	26	86	34	35	1.03	206
10	6/2/00	25	81	38	34	0.90	95
11	6/2/00	34	83	34	35	1.03	111
12	6/2/00	58	85	32	35	1.12	111
1	7/17/00	48	50	22	25	1.14	87
2	7/17/00	44	56	20	23	1.21	107
3	7/17/00	47	51	24	24	1.02	90
4	7/17/00	41	42	23	22	0.96	116
6	7/17/00	23	78	30	28	0.92	148
7	7/17/00	9	83	29	29	1.00	139
8	7/17/00	47	84	39	32	0.82	110
9	7/17/00	6	90	33	28	0.86	166
10	7/17/00	26	82	38	32	0.85	155
11	7/17/00	47	82	39	26	0.67	151
12	7/17/00	23	85	44	29	0.67	119
1	8/31/00	54	44	27	23	0.84	79
2	8/31/00	43	52	30	22	0.73	99
3	8/31/00	50	53	23	20	0.85	97
4	8/31/00	43	53	31	23	0.78	116
6	8/31/00	51	71	25	34	1.37	71

TABLE 8A (CONT) – DATA FROM ANALYSES ON MSW FROM COLUMN STUDY

Column	Sample Date	Moisture (%)	VS (%)	Lignin (%)	Cellulose (%)	C/L	BMP (mL/g)
7	8/31/00	25	87	33	42	1.29	111
8	8/31/00	39	85	30	47	1.57	115
9	8/31/00	23	83	32	43	1.34	125
10	8/31/00	35	71	30	39	1.29	115
11	8/31/00	45	74	32	34	1.05	104
12	8/31/00	21	71	36	37	1.03	96
1	12/5/00	53	51	22	21	0.93	75
2	12/5/00	45	59	19	26	1.37	137
3	12/5/00	48	39	17	12	0.69	47
4	12/5/00	47	50	17	14	0.82	81
6	12/5/00	49	73	40	22	0.57	84
7	12/5/00	33	80	33	29	0.88	89
8	12/5/00	40	77	33	28	0.85	56
9	12/5/00	25	85	38	33	0.88	90
10	12/5/00	35	80	28	35	1.28	102
11	12/5/00	51	74	34	34	1.00	74
12	12/5/00	24	76	36	44	1.23	96
1	2/15/01	50	59	25	25	1.01	40
2	2/15/01	41	58	25	22	0.90	102
3	2/15/01	43	46	18	17	0.96	29
4	2/15/01	43	47	18	16	0.90	45
6	2/15/01	48	63	20	31	1.54	50
7	2/15/01	27	79	28	42	1.54	80
8	2/15/01	49	73	26	35	1.33	38
9	2/15/01	29	81	34	36	1.07	133
10	2/15/01	42	70	27	30	1.10	88
11	2/15/01	44	68	27	36	1.47	50
12	2/15/01	23	81	27	42	1.62	106

TABLE 9A – DATA FROM ANALYSES ON LEACHATE FROM COLUMN STUDY

Column	Date	pH	TOC (mg/L)	COD (mg/L)	BOD (mg/L)	TKN (mg N/L)	Total P (mg/L P)	Alkalinity (mg CaCO3/L)	TSS (mg/L)	VSS (mg/L)	TDS (mg/L)
1	4/09/00	5.94	26650	112750	27150	1211	10.41	13272	378	235	53765
2	4/09/00	4.73	3221	105600	5338	3	0.68	53	137	126	140
3	4/09/00	5.63	28225	116000	22775	968	8.06	12317	121	81	51120
4	4/09/00	7.81	25410	117950	27300	15	44.33	13272	475	324	61595
1	5/11/00	5.64	22437	117600	59550	1	14.88	11982	416	244	21750
2	5/11/00	4.28	14100	115400	610		1.91	0	98	76	905
3	5/11/00	5.58	22080	140500	50300	118	5.31	12821	293	217	25555
4	5/11/00	5.77	8317	118550	39900	122	37.91	12731	1285	1010	25895
6	6/05/00	6.24	6614	87033	39740	424	7.95	2047	219	152	19725
8	6/05/00	7.03	690	86300	1730	30	1.38	139	96	100	775
10	6/05/00	7.21	125	82400	5377	1	2.94	32	8	5	260
11	6/05/00	5.81	6804	82300	13450	573	12.09	1589	209	181	21315
1	6/29/00	5.47	29143	94567	44325	1316	9.06	12421	357	208	47485
2	6/29/00	7.24	419	499	47	364	6.45	682	194	184	2755
3	6/29/00	1.94	28153	93000	42075	1344	5.10	0	5640	434	2200
4	6/29/00	5.94	28497	88033	55325	1848	6.94	17145	36	36	77960
6	7/5/00	5.64	891	400	299	112	1.23	490	402	38	2520
8	7/5/00	6.19	3429	9467	2888	504	0.00	160	67	53	2560
10	7/5/00	4.83	368	900	508	168	1.46	11	790	38	3035
11	7/5/00	5.47	1279	3200	1410	168	1.56	1877	480	370	11755
6	8/2/00	5.94	1203	2767	116	57	0.24	629	66	56	
8	8/2/00	7.09	11	62	5	3	0.24	128	114	72	
10	8/2/00	4.08	591	85	138		0.09	0	10	10	
11	8/2/00	5.28	3894	1100	485	195	0.11	2175	62	51	
1	8/7/00	5.52	29140	100300	52418	1523	0.30	20738	1450	851	
3	8/7/00	5.55	29380	97133	48068	1648	0.00	16025	64	43	
4	8/7/00	5.91	31573	96067	50668	1612	0.60	20152	51	39	
1	9/12/00		28583	96000	42999	1839			214	119	45340
3	9/12/00		28920	946000	40049	1582			126	99	54100
4	9/12/00		35233	114300	41049	722			2190	1985	71470
6	9/12/00		3078	8800	3364	155			543	239	1519
8	9/12/00		3777	138	18	30			97	49	390
10	9/12/00		4163	9600	2872	400			60	48	10590
11	9/12/00		13397	35800	15216	549			63	35	31710
1	1/31/01	5.49	28503	91745	48476	1960	0.85	13866	248	120	
3	1/31/01	5.49	29383	53787	49530	1758	3.89	14693	697	339	
4	1/31/01	5.57	34520	108255	51639	2206	0.99	18339	1513	338	
6	1/31/01	6.45	3235	6638	4827	224	0.36	2538	213	143	
8	1/31/01	6.51	85	213	31	3	0.30	32	244	152	
11	1/31/01	5.26	14727	32000	22489	560	0.44	4627	137	45	

TABLE 11A – ION DATA FROM ANALYSIS OF LEACHATE FROM COLUMN STUDY

Column	Date	Cations (mg/L)					Anions (mg/L)				
		NH3-N	Ca++	Mg++	K+	Na+	Cl-	NO3-	NO2-	PO4-P	SO4-S
1	4/09/00		2903	1237	1016	1236	2608		544		
2	4/09/00		21	7		8	75	152	14	2	208
3	4/09/00	648	2498	1229	937	1180	2512	196	371	12	401
4	4/09/00		4535	1189	1041	1380	3120		62	11	325
1	5/11/00	1524	4011	1166	1004	1097	2492	72	579		480
2	5/11/00	73	201	38		49	132		18		
3	5/11/00	1219	5344	1478	982	1311	2908		639		488
4	5/11/00	1221	5116	1386	1007	1206	3014		240		480
6	6/05/00	1768	4161	1188	1007	1124	2601		629		533
8	6/05/00		132	29	23	45	143				234
10	6/05/00	428	4898	1354	999	1092	3074		663		565
11	6/05/00	572	6495	1681	1405	1519	4281		415		
1	6/29/00		1261	233	385	552	1647		31		1150
2	6/29/00		186	36	36	120	172		15		251
3	6/29/00		77			106	140				
4	6/29/00	72	348	69	147	199	2210				1456
6	7/5/00		69	19	13	54	82				180
8	7/5/00	223	889	163	326	396	1205		20		708
10	7/5/00	134	875	148	301	439	1202		21		669
11	7/5/00	98	385	72	116	234	471		16		430
6	8/2/00	1073	557	47	119	410	476		3		467
8	8/2/00		31	7	7	30	166		1	129	345
10	8/2/00		104	3	2	17	32			163	4
11	8/2/00	3250	785	95	225	582	807			78	384
1	8/7/00	1309	4643	1262	1123	1985	2351	5	714		498
3	8/7/00	917	5920	1610	1113	2263	2675		768		479
4	8/7/00	524	7526	2002	1564	2860	211		153		137
1	9/12/00						2384		549		457
3	9/12/00						2865		430		489
4	9/12/00						4127		501		499
6	9/12/00						1329		10		203
8	9/12/00						958				946
10	9/12/00										
11	9/12/00						3596		137		1149
1	1/31/01	1203	5177	1311	1099	2004	2357				
3	1/31/01	1025	5701	1516	1182	2515	2741		5		
4	1/31/01	1055	7099	1923	1558	3170	4299	292	6		
6	1/31/01	0	1028	273	539	1320	1887		854		14
8	1/31/01	1	39	8	9	28	129	2		21	25
11	1/31/01	355	4552	542	1252	2497	4306				

TABLE 12A – DATA FROM ANALYSIS OF METALS IN LEACHATE FROM COLUMN STUDY

Column	Date	Zn (mg/L)	Cu (mg/L)	Ni (mg/L)	Cd (mg/L)	Pb (mg/L)	Cr (mg/L)	Fe (mg/L)	Mn (mg/L)
1	4/09/00	13.74	0.23	1.95	0.10	0.88	0.49	275.20	43.53
2	4/09/00	0.44	0.07	0.64	0.02	0.68	0.00	16.60	0.14
3	4/09/00	17.95	2.29	2.26	0.48	1.71	0.26	7.87	32.50
4	4/09/00	39.25	0.74	2.47	0.49	1.05	0.57	697.35	33.26
1	5/11/00	12.10	0.08	2.78	0.06	0.59	0.14	472.03	39.77
2	5/11/00	1.74	0.12	0.43	0.06	0.57	0.04	29.93	1.32
3	5/11/00	24.40	4.06	3.59	0.58	4.29	0.14	5.97	38.30
4	5/11/00	46.80	2.20	3.60	1.57	1.12	0.23	119.60	33.93
6	6/05/00	21.03	0.71	1.03	0.06	0.75	0.91	159.20	13.60
8	6/05/00	0.16	0.01	0.42	0.00	0.42	0.05	12.67	0.73
10	6/05/00	0.12	0.00	0.01	0.00	0.00	0.01	0.14	0.04
11	6/05/00	29.60	0.09	0.65	0.02	0.24	0.69	164.77	17.40
1	1/31/01	27.00	0.16	1.92	0.12	0.92	0.32	20.93	64.00
3	1/31/01	45.00	0.17	2.22	0.15	0.77	0.34	1036.00	63.00
4	1/31/01	63.00	0.63	3.07	1.85	0.86	0.36	894.00	74.00
6	1/31/01	0.43	0.00	0.19	0.02	0.11	0.06	11.06	5.05
8	1/31/01	0.20	0.00	0.00	0.00	0.02	0.02	0.13	0.08
11	1/31/01	108.00	0.16	1.71	0.07	0.62	0.65	142.00	0.77

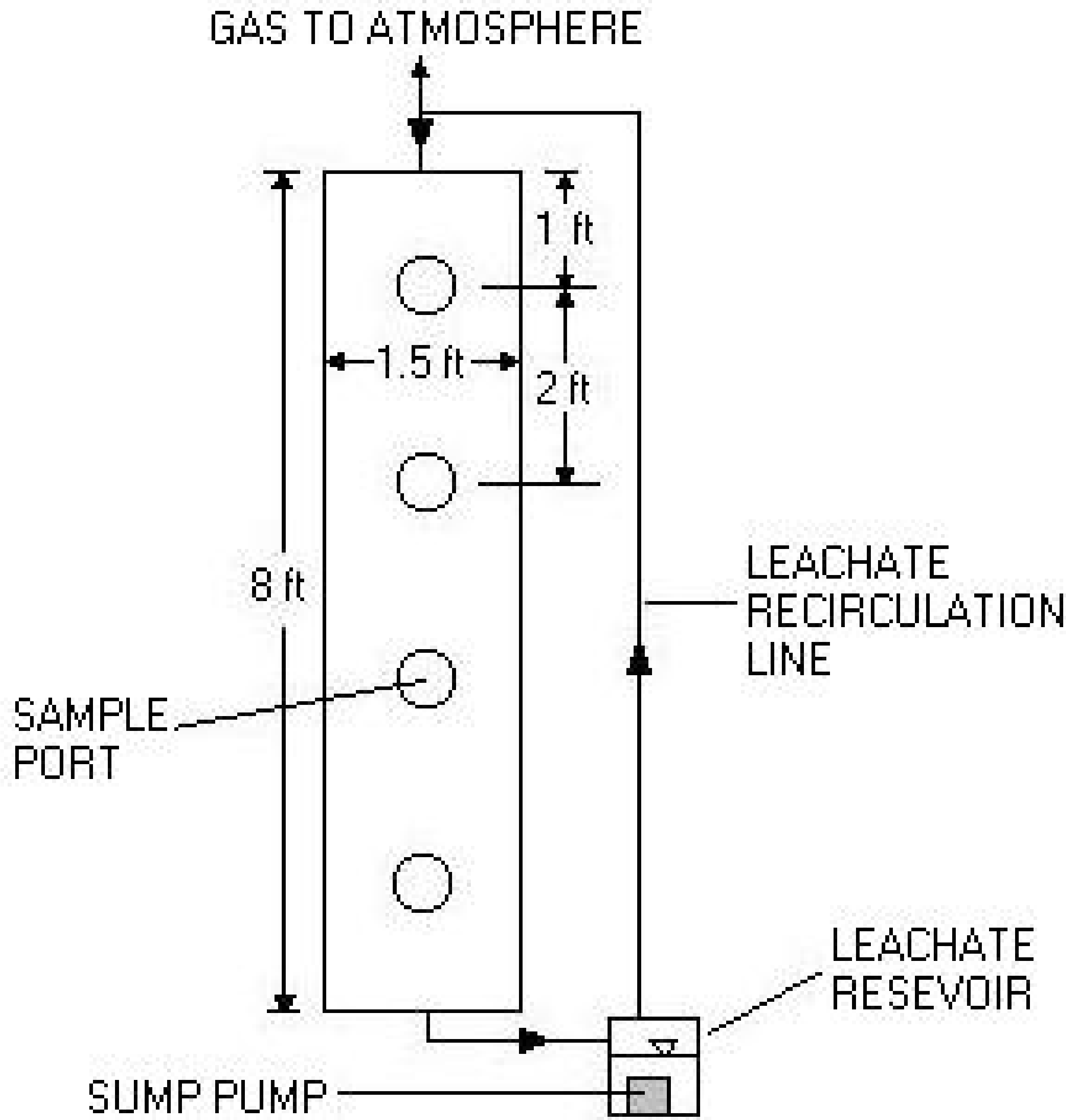


FIGURE 2A – CONCEPTUAL DRAWING FOR COLUMN BIOREACTOR

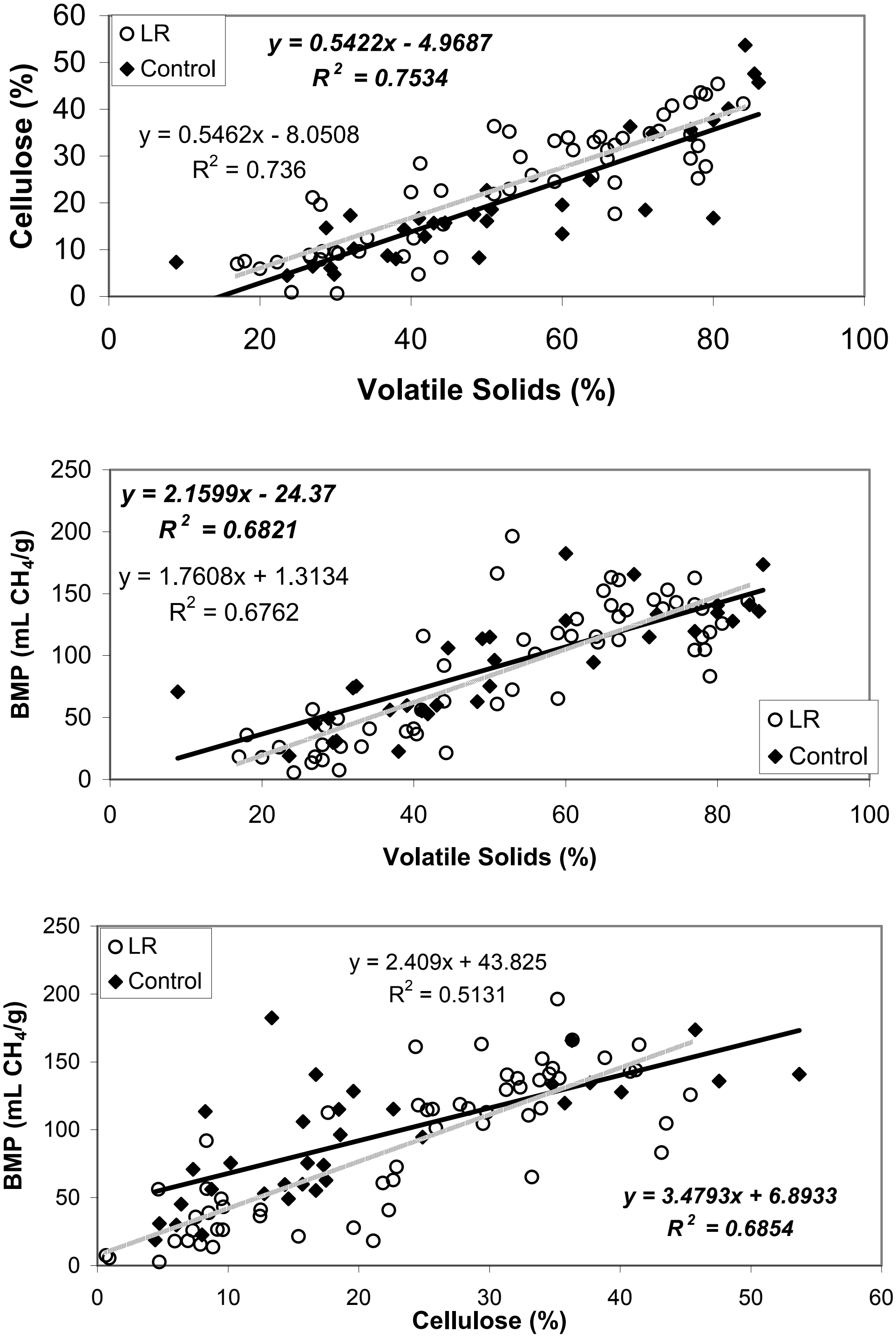
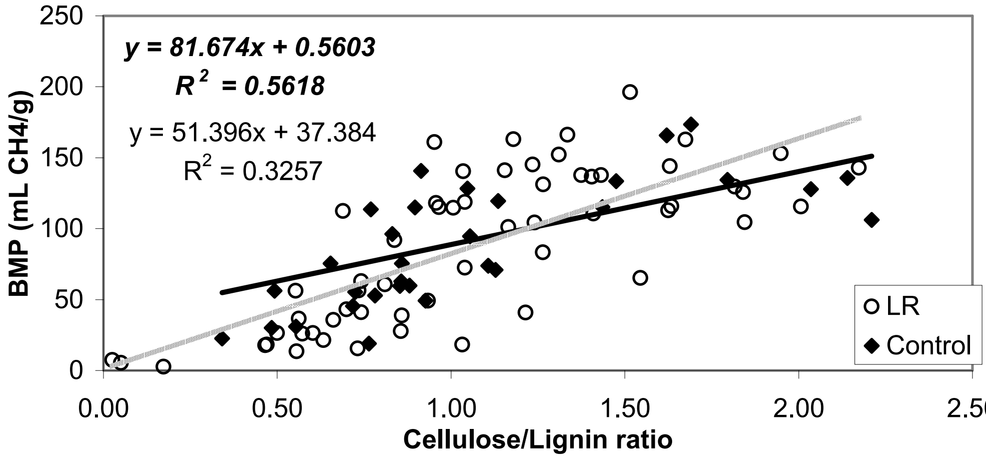


FIGURE 3A – EFFECT OF ENHANCED DEGRADATION ON CORRELATIONS FOR LEACHATE RECIRCULATION DATA



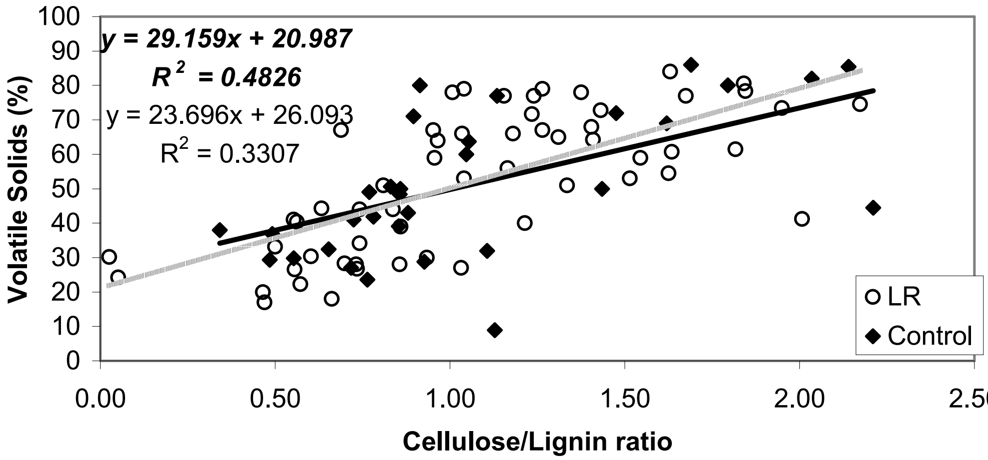


FIGURE 3A (CON'T) - EFFECT OF ENHANCED DEGRADATION ON CORRELATIONS FOR LEACHATE RECIRCULATION DATA

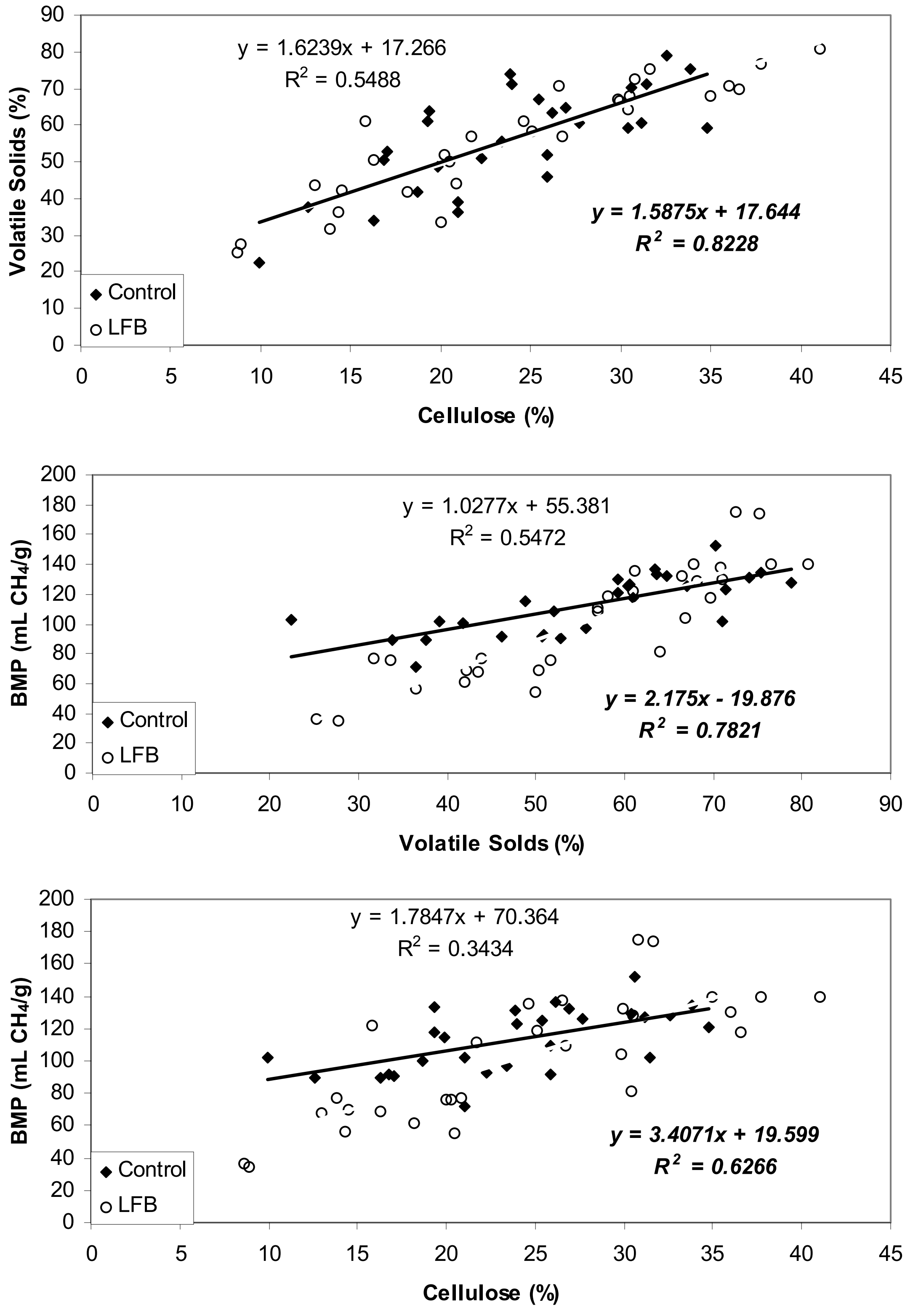
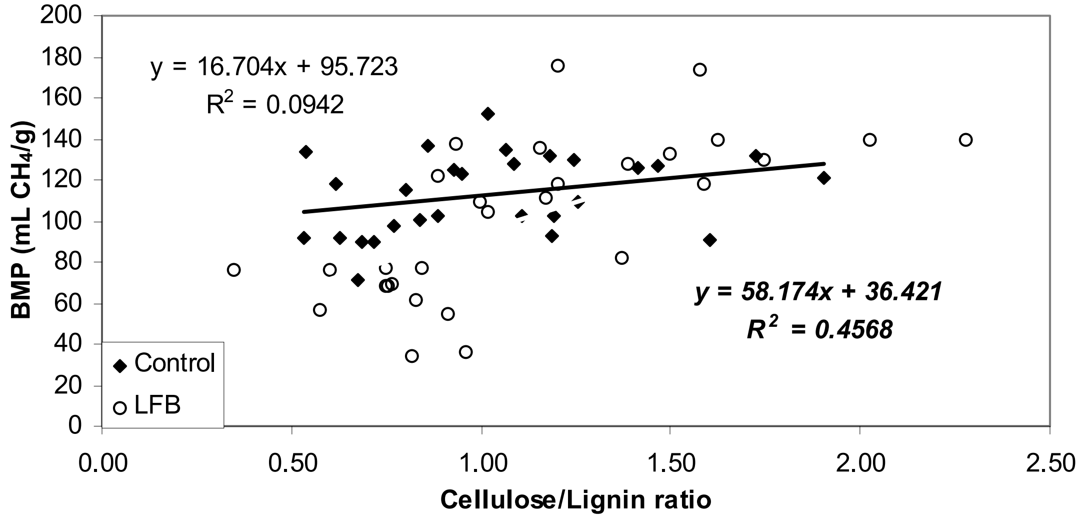


FIGURE 4A – EFFECT OF ENHANCED DEGRADATION ON CORRELATIONS FOR BIOREACTOR DATA



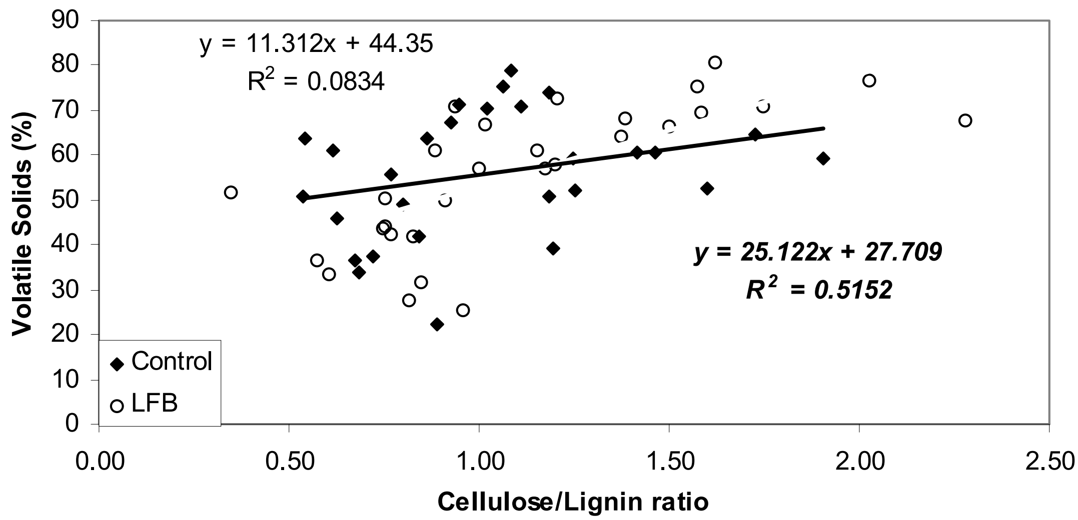


FIGURE 4A (CON'T) – EFFECT OF ENHANCED DEGRADATION ON CORRELATIONS FOR BIOREACTOR DATA

VITA

Brad David Shearer was born on November 1, 1976, in Salem, Virginia. He graduated from Salem High School in June of 1994. In August 1994, he entered the College of Arts and Sciences at Virginia Polytechnic Institute and State University as a physics major. In 1996, he transferred to the College of Agriculture and Life Sciences, where he graduated Magna Cum Laude in 1998 with a B.S. in Environmental Science. In May 2001, he will be graduating with an M.S. in Environmental Engineering and begin work in August as a engineering consultant in the remediation industry.