THE STATUS OF AEROBIC LANDFILLS IN THE UNITED STATES

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SUMMARY: Bioreactor landfills are a new and emerging trend in waste management in the US. Now a routine practice, adding moisture to landfilled wastes has multiple benefits, including an increase in waste degradation, which can lead to a reduction in risk. Although in the early stages of application in the US, the addition of air along with moisture holds further promise, for it has been demonstrated in laboratory, pilot and field-scale projects that this approach can increase waste settlement, lower leachate treatment costs, reduce methane and odor production. Based on these studies as well as aerobic landfill applications overseas , a number of full-scale projects and several patents have been established. This paper reports on the current status of aerobic landfills in the US, including the history and future of aerobic landfilling in the US, the challenges ahead, and a summary of current aerobic landfill studies and full-scale projects.

1. INTRODUCTION

A new and emerging trend in waste management in the United States is to operate a landfill as a bioreactor. Bioreactor landfills differ from conventional landfills in that they are operated in a controlled fashion to create an *in-situ* waste environment more conducive to degradation by injecting moisture and/or air to the landfill. The Solid Waste Association of North America (SWANA) defines the bioreactor landfill as any "landfill or landfill cell where liquid or air is injected in a controlled fashion into the waste mass in order to accelerate or enhance biostabilization of the waste."

The practice of controlled moisture addition (usually as leachate) is becoming fairly routine at many US landfills. Further, recognizing the benefits of organics composting and wastewater treatment, the simultaneous addition of air and moisture holds promise as well, whereby additional benefits (increase waste settlement, lower leachate treatment costs, reduced methane production) can be obtained. Yet, air injection has not been extensively practiced for aspects concerning appropriate operational techniques (increased waste temperature and gaseous emissions) remained. To address these, laboratory, pilot and field-scale projects, have and are being conducted to more thoroughly evaluate this technology, leading to a number of full-scale projects.

2. HISTORY OF AIR INJECTION IN THE US

In the late 1960's, the Bureau of Solid Waste Management at the US Environmental Protection Agency (EPA) funded studies to develop and evaluate new technologies to improve or accelerate the handling of the Nation's solid waste (introduction written by Vaughan in the Merz and Stone (1970) report). Merz and Stone (1970) operated several model landfill cells to evaluate the impact of water and air injection on landfill operation and subsequent emissions. Consequently, they operated the first reported US-based study in which air addition to landfills was evaluated. During the course of their four-year project, air was intermittently added to a model cell .For example, between days 28 and 69 of operation, air addition was cycled, turned on for 0.5 hrs and then off for 5.5 hrs. In the aerated cell, high temperatures (up to 90^{o}C), smoke, odor problems, and occasional fires were observed. At the bottom of the aerobic cell, the temperatures were so high that all installed thermisters were destroyed. During their study, the only water added to the aerobic cell was that equivalent to the amount of expected rainfall, thus the waste was rather dry (moisture content was always less than 50%, by weight, often around 40%) and was most probably the reason for the temperature control issues. The aerobic cell settled almost 50% more than the anaerobic cells and little of the waste recovered from the cell at the end of the project was identifiable, besides some non-biodegradable matter, such as plastics, rubber and metal. Some scorched paper was also recovered. The off-gas composition, when the blower was operational, indicated aerobic microbial activity was occurring and generally consisted of 10% oxygen, 70 – 80% nitrogen and 10 – 20% carbon dioxide. Methane production was minimal during aeration.

Although the Merz and Stone (1970) study indicated aeration of solid waste would accelerate waste degradation and settlement of landfills, concerns regarding the high temperatures and potential for in-situ fires remained and ultimately delayed further research in the aerobic landfill area. In the early 1990's, Stessel and Murphy (1992) revisited laboratory-scale research involving the addition of air to landfills in a study aimed at making landfills more economically sound and environmentally friendly. Their work was built around the concept of landfill mining. Mining of a landfill would allow for it to become a more sustainable entity, as all non-biodegradable materials could be removed and recycled, subsequently resulting in an area that could be reused. However, it was determined that landfill mining would only be productive if enhanced waste degradation occurred (Stessel and Bernreuter, 2001), which prompted them to reconsider the concept of aerobic landfills. Because little literature regarding optimal leachate and air injection rates existed, Stessel and Murphy (1992) operated a series of lysimeters evaluating different injection rates, as well as evaluating the differences between anaerobic and aerobic conditions. Their results showed that aerobic conditions greatly enhanced waste decomposition (in comparison to anaerobic conditions) and thus the settlement potential was high. An optimal waste moisture content of 75%, by weight, was maintained throughout the study, which is much higher than that used in the Merz and Stone (1970) study. Unlike Merz and Stone (1970), no temperature concerns were reported, most probably a result of the high water content in each of their systems. The work by Stessel and Murphy (1992) confirmed the advantages associated with aerating landfills observed by Merz and Stone (1970) and served as the premise for the operation of a subsequent demonstration and full-scale projects. As temperature control was a major issue associated with aerobic landfills, care was taken in these studies to apply a properly balanced mixture of leachate and air to mitigate fire potential.

Based on the work by Stessel and Murphy, larger-scale tests began, whereby portions of landfills in Georgia and South Carolina were aerated (ATI 1997; ATI 1999; Hudgins and Harper 1998). ATI (1997) operated an aerobic landfill in an active 3.2-ha portion of the Columbia County Baker Place Road Landfill in Georgia. The landfill was 3 – 3.7 m deep. Air was injected over an 18-month period through vertical wells as well as the leachate collection system. The following are benefits reported by Hudgins and Harper (1998) as compared to pre-startup (background) conditions:

- Increased the solid waste biodegradation rate by 50%
- Decreased the BOD of the leachate by 65 - 90%
- Decreased methane production by 50 - 90%
- Decreased toxic organic levels by over 90%
- Decreased leachate production by 86%

Further, LFG samples were collected the “aerobic” and “anaerobic” portions of the landfill. Analyzed by the University of Florida, results indicated that the total non-methane organic compound (NMOC) concentrations in the aerobic portions averaged 37.0 ppmv (as hexane). The total NMOC concentrations in the "anaerobic" area averaged 146.9 ppmv (as hexane), a difference of 75%. (Hudgins, 2000). In 1997, a 1-ha aerobic test cell was operated at the Live Oak Landfill in Atlanta, GA for 9 months. The landfill cell was 8 m deep. Injection wells were installed at 18.3-m spacing. Both of these tests demonstrated that operating a landfill aerobically significantly degrades solid waste at a faster rate than under anaerobic conditions, reduces the volume and strength of the leachate, and decreases the amount of methane gas generated. Waste samples collected from waste excavations, the largest fraction (over 50%) appeared “as a suitable soil/compost material with a sufficient moisture content” (30%) (Smith, 1998). The compost, which passed through a 1- to 2-cm screen, was stable, with little odor. Plastic products, metals, and glass occupied over 30% of the remaining materials, with inert materials as the balance. Lignin-containing materials (e.g. wood and paper) degraded slightly. Laboratory analysis showed that soluble salts, metals, and pH were within safe ranges. Also, no pathogens were detected in the materials. With respect to the degree of compost activity, oxygen uptakes in waste samples collected from one site ranged from 0.167 to 0.351 mg per gram of volatile solid per hour (VSPH). Respiratory measurements of this type performed on compost have determined that oxygen uptake rates of less than 0.5 mg of oxygen per gram of VSPH indicate stable compost (Smith, 1998)

This work as well as international efforts prompted other laboratory and pilot studies to evaluate and optimize the aerobic landfill technology. (Berge, 2001; Smith et al., 2000; Borglin et al., 2004; Daniels et al., 2005a; Hazen et al., 2000). To interpret results from these studies, several researchers have described simulations of waste degradation and air and liquids flows in aerobic landfills (Daniels et al., 2005b; Hazen et al., 2000). Further, this data had led to new ideas using aerobic processes. For example, a US landfill (New Jersey) is conducting aerobic studies as part of a planned 75-acre landfill mining/ cell reuse strategy, referred to as a “sustainable landfill.” (Barstar, 2003, 2003 Hudgins, et al).

The aerobic bioreactor landfill process has been patented. In October 1996, a patent was granted for “improvements to landfill mining” (US Patent No. 5,564,862). Since then, American Technologies, Inc. (Hudgins et al., 2000) and Environmental Control Systems (Environmental Control Systems, 1999) have received patents for their aerobic landfill systems (US Patent Nos.

6,024,513 and 5,888,022, respectively). Waste Management, Inc. holds a patent for a sequential aerobic/anaerobic system in which aerobic and anaerobic conditions are cycled (US Patent No. 6,283,676, Hater and Green, 2001).

3. STATUS OF AEROBIC LANDFILL STUDIES IN THE US

This research and activity has led to multiple aerobic bioreactor studies and projects. Table 1 provides a listing of known demonstration and full-scale aerobic landfills in the US, including one aerobic landfill that has been operating in Toronto, Canada for 18 years (Donlands). The motivation for operating these sites aerobically are varied, but generally consist of remediation of surface and groundwater impacts (Williamson Co.), reduction of leachate volume (Williamson Co.) elimination of methane and other odorous gases (Yolo Co, Donlands Landfill), rapid stabilization of the waste (Outer Loop, Williamson Co., Marquette), site redevelopment (Rio Nuevo), and evaluation of design and operating parameters (Live Oak, New River Regional Landfill). Provided below are brief descriptions of several these studies and projects.

Table 1. Full Scale Aerobic Landfills in North America.

Landfill Name	**Landfill City**	**Start Date**	**End Date**	**Wetting Method**	**Scale**
Aiken County Landfill	Langley, SC	1998	1999	Injection	Demonstration
Chemung County SLF	Elmira, NY	1992	1996	Spray	Full
City of Santa Clara LF	Santa Clara, CA	1969	Unknown	Unknown	Demonstration
Columbia County	Grovetown, GA	1997	2000	Injection	Demonstration
Cumberland County Solid Waste Complex	Deerfield Township, NJ	2003	2007	Vertical Injection Wells	Full
Greater Albany SLF	Albany, NY	1989	1995	Spray	Full
Hamilton County LF	Chattanooga, TN	1999	Unknown	Injection	Full
Marquette County Landfill	Marquette County, MI	2002	Ongoing	Injection	full
Metro Recycling and Disposal LF	Franklin , WI	Unknown	Unknown	Injection	Separate Cell
New River Regional LF	Raiford, FL	2002	Present	Injection	Full
Ontario County SLF	Canandaigua, NY	1998	1998	Spray	Full
Outer Loop RDF	Louisville, KY	2002	Present	Injection	Full
Plantation Oaks	Sibley, MS	Unknown	Unknown	Unknown	Unknown

LF					
Sullivan County LF	Thompson, NY	2001	2001	Spray	Full
Williamson County LF	Franklin, TN	2000	Present	Injection	Full
WMI-Live Oak Landfill	Conley, GA	1997	1999	Injection	Demonstration?
Yolo County Landfill	Woodland, CA	2000	Present	Injection	Full
Donlands Landfill	Toronto, ON	~1988	Unknown	Rain Percolation Through Cover	Full
Rio Nuevo Landfill	Tucson, AZ	2001	2006	Injection	Full

In 2000, aerobic landfilling began in Williamson County, TN and continues to be operated today (CEC, 2006). The bioreactor was designed and retrofitted into the landfill to primarily reduce leachate volume and environmental impact of a RCRA Subtitle D landfill. (liner and leachate collection system) This 2.4-ha site is 12 m deep and was constructed with steep side slopes (1.5:1). The retrofit construction used vertical well clusters reaching 3, 6, and 9 m at 15 m spacing to inject air and leachate. Air injection averaged 0.8 m^3/min per well. Temperatures as high as 74°C were reported. Settlement reached 5-10 % of the overall landfill height over a 5-year period. Waste respirometry data showed less oxygen uptake per gram of dry matter of solid waste, as compared to before aeration, resulting in a 45% uptake reduction. In addition, Total Volatile Solids (TVS), Lignin, Cellulose, Biochemical Methane Potential (BMP), and Total Solids, all indicators of waste toxicity, were reduced 55%, 40%, 47%, 9%, and 4%, respectively. Also, there has been a statistically significant drop in BOD/COD ratios over the past four years. Since 2000, the system has received virtually all of the 8 million-plus gallons the landfill cell has produced, with no side slope failures. In Tucson, AZ, several aerobic landfill tests have been conducted to recover sites occupied by older landfills. The 0.10-ha pilot test at the Rio Nuevo Landfill began in late 2001. Air and liquid injection through vertical wells lead to a one-foot settlement in five months. Air injection rates varied between 1.4 and 8.5 m^3/min. Injection of air and water was used to control temperature which rapidly increased to 71°C after a few days of operation. Using this data, a full-scale aerobic landfill system has been implemented, and is currently operating.

The City of Toronto has been operating an aerobic landfill for over 25 years. Known as the Donlands Landfill, this system has not only virtually eliminated methane gas, but the landfill surface has settled over 30% (5 m/15m). (Beatty and Associates 2000). In addition, the system has eliminated odor emissions and allowed vigorous vegetation growth and reforestation of the cover (4-cm diameter trunks). The New River Regional Landfill serves as host to a 4-ha bioreactor demonstration cell equipped with 134, 5-cm diameter vertical injection wells that permit air and liquid injection. These wells were placed in clusters of three reaching 6, 12, and 18 m in depth. The site was covered with 1-mm textured low density polyethylene. Air injection has been practiced periodically since 2003 to explore air permeabilities, air emissions resulting from air injection, and the impact of leachate recirculation on air flow (Jain et al., 2005;

Powell et al., 2006). Air at flow rates of 1-1.4 m^3/min was observed to impact monitoring wells 15-17 m away. Oxygen content was consistently less than 3 % in these wells. Temperatures increased from 50^o to almost 77^oC over a period of approximately 20 days, 4 m away from the injection point and at a depth of 4.5 m. Consequently, air flow was interrupted and leachate injection commenced to control the temperature. Interestingly carbon monoxide (CO) was observed during air injection; however there was no reason to believe that a fire existed. The presence of CO was attributed to biological oxidation processes. Air permeabilities were reported to be between 1.6×10^{-13} and 3.2×10^{-11} m^2 and decreased with depth. Permeabilities declined by a factor of five following injection of liquid.

Lastly, it is important to recognize that data collected from international has influenced the development of US aerobic landfill approaches. For example, the Fukuoka Method is one aerobic approach that is being widely applied across Japan. This Method utilizes the self-purifying capacity inherent in ‘nature’ to stabilize waste materials (Hanashima 1999) such that; the quality of leachate improves significantly and more rapidly than in anaerobic conditions (based on BOD reduction). The Japanese version of the aerobic landfill appears to be simple to construct and operate, allowing a high degree of freedom in the selection of materials for pipes and accessories. Further, at some sites, air delivery pipes are made of bamboo. Investigations carried out by Heyer et al.[i] during *in situ* aeration of the landfill in Kuhstedt (Germany) after 14 years since it had been closed, revealed that methane content in the landfill gas decreased from around 50% to less than 1.5% a month since starting the aeration (Heyer 2001). In biogas samples taken from the landfill gas system installed in the landfill in Modena (Italy), around 10% methane was found after ca. 50 h of periodic aeration (Cossu, 2001). Further, the 'Bio-Puster Method' (a patented landfill aeration system) has been used in Austria since 1991, and aerobic studies have been performed in Simcoe County, Ontario (1999) and in France and Australia. In 2000, a Dutch study of selected methane gas control technologies ranked landfill aeration of waste as the highest and most economical. (Luning, 2000) A technical review paper prepared by Stessel and Murphy indicated that over 30 studies and/or aerobic projects have been implemented worldwide.

In general, conclusions from these operations indicated more rapid waste decay than anaerobic bioreactors. In addition, the high temperatures observed can result in pathogen destruction. Further, a reduction in leachate contaminants and volumes occurs and significant reductions in methane concentrations has been observed. Lastly, airspace recovery has been enhanced. Yet, additional liquid beyond that required for anaerobic bioreactors must be added for reactions to occur, and temperature can be controlled by modulating liquid and air flow rates. Other reported advantages of operating the landfill aerobically rather than anaerobically include odor reduction, decreased metal mobility, and reduced environmental liability (ATI, 1997; Berge et al., 2005; Hudgins and Harper, 1998; Read et al., 2001).

4. MOTIVATIONS AND CHALLENGES ASSOCIATED WITH OPERATING AEROBIC LANDFILLS IN THE US

The benefits of aerobic landfills can motivate landfill owners. However, as discussed below, there are also many challenges associated with their application. To address these challenges, the designer and operate should first view the aerobic landfill as a unique biological system, and independently from other bioreactor designs Although, there are common features (e.g. leachate addition), aerobic systems are generally more dynamic, thus design approaches and operating protocols will most likely be different. As compared to other types, aerobic bioreactors:

- operate at different moisture application rates;
- due to rapidly decaying waste, liquid movement within the waste varies continually;
- waste decay occurs via different biological pathways and kinetics; and,
- heat transfer and liquid control is more critical.

There are other differences as well. For example, horizontal liquid application may work effectively in anaerobic bioreactors, for it is assumed that the piping slope is constant, and thus evenly-distribution of liquids within the waste occurs. However, in aerobic systems, waste settlement is more rapid and pronounced. As such, horizontal leachate application may not be appropriate due to the rapid change in relative piping slope, thus a possible uneven distribution of liquids. To address this, aerobic systems can use vertical wells that are less likely to be affected by rapidly settling waste. This is an important design consideration, for “targeted” moisture application is critical.

Another challenge with aerobic systems is to determine the amount of data to be collected. Although there are common biological, chemical, and physical process inherent to bioreactors, there is no “one-size-fits-all” design approach. Each bioreactor system should be designed to meet the goals of the landfill owner, while recognizing each landfill’s physical, environmental, and regulatory setting. Thus, the data collection phase should be commensurate with the owners goals. For example, the Donland aerobic system operated at lower than normal air flow rate, yet still degrade waste and provide significant settlement. As such, the landfill owner realized lower operating costs. However, for this site, these benefits were derived without an extensive data collection nor aerobic bioreactor design effort. Instead, the increased LFG extraction from the landfill created a negative pressure in the landfill and thus introduced air through the permeable cover at a rate that promoted aerobic conditions within the waste. At the Williamson County project, only primary data (waste temperature, O2, CH4, CO2 readings) were required to be collected. As such, the owners goals are being met. Although additional support data (e.g. analyses for NMOC, N_2O, pH,) should be collected where practical to better understand certain aspects of aerobic science, this project could have been less attractive, from a economic view, if an extensive list of support data had been required by regulators

During aerobic degradation of MSW, biodegradable materials are converted mostly to carbon dioxide and water. Little, if any, methane is produced. This may be viewed as either an advantage or disadvantage, depending on the desires of the landfill owner. Although methane is an explosive “greenhouse gas” that has also been linked to cancer formation in human beings, it can be used as a source of energy. However, if it cannot be efficiently or economically controlled, collected, or used, its production can be a local hazard and global environmental concern. Thus, operating aerobically would alleviate any concern or risk of methane emissions.

Further, odors often associated with anaerobic systems, such as hydrogen sulfide and volatile acids, are reduced in aerobic bioreactor landfills. In some cases, though, aerobic processes can have an earthy smell odor associated with them and/or could produce odorous compounds sometimes found in aerobic composting such as methanethiol, which has a pungent sulfide odor (Miller, 1992).

Aerobic landfills also have the potential to reduce leachate management issues and costs. The aerobic process generates a considerable amount of heat, (aerobic biodegradation releases approximately 3600 cal/gm substrate oxidized) leading to observed elevated in-situ temperatures as high as 71^{o}C (Powell et al., 2005). The elevated temperatures increase evaporation, which results in a significant loss of leachate. As a result, there is less leachate to manage (Read et al., 2001) which may correspond to significant leachate treatment savings. At the Williamson County site, over 8 million gallons of leachate (100%) have been treated, with no major slope failure. Further, the solid waste environment during aerobic degradation has a fairly neutral pH (Stessel and Murphy, 1992), which decreases metal mobility. Volatile organic acid production is decreased in aerobic bioreactors because the anaerobic fermentation processes are limited. However, volatile acid and methane production may still occur in anaerobic pockets within the landfill.

Additionally, operating the landfill aerobically results in removing some anaerobically recalcitrant compounds in both the leachate and waste, such as lignin. Also, other leachate constituents have the potential to be removed to a greater extent in aerobic conditions, such as BOD, COD and ammonia-nitrogen. Ammonia-nitrogen leachate concentrations generally increase when stimulating microbial activity in landfills. It has been suggested that ammonia-nitrogen may be one of the most significant long-term pollution problems in landfills (Berge et al., 2005; Kjeldsen, 2002). Many of the nitrogen transformation/removal process are favored by aerobic processes, including nitrification and ammonia air stripping or volatilization. Aerating a landfill has shown to induce nitrification and sequential or simultaneous denitrification, resulting in complete removal of nitrogen (Berge et al., 2006). Removing the nitrogen inside the landfill is advantageous, as it alleviates extra costs associated with external treatment. If the successful removal of nitrogen, BOD and COD occurs, any environmental risk associated with a potential accidental release of leachate is reduced significantly and post-closure care monitoring requirements may also be reduced.

Lastly, landfill settlement occurs to a greater extent and at a faster rate than in anaerobic systems. Over time, this increased settlement equates to a greater landfill capacity and can thus potentially result in more revenue for landfill owners and may reduce the number of new landfills needed. (e.g. Donlands site)

As with engineered biological systems, such as anaerobic and aerobic landfills, maintaining control, monitoring the process, and evaluating treatment performance are essential; however, as every landfill is unique, these tasks can be challenging. In aerobic systems, one major challenge is the distribution of air to target areas within the waste such that degradation is maximized. At the start of each project, effective air and liquids flow patterns are established. However, due to waste heterogeneity and changing waste characteristics, flow patterns can change over the course of the application. This can be beneficial for aerobic treatment for changing patterns re-directs flow, thus maximizing air and liquids “coverage area.” However, the system operator needs to be able monitor these changing patterns to ensure that the proper amounts of air and liquids are applied. In addition, the rate of mass transfer of oxygen from the gas phase to the liquid in large-scale systems (thus the amount of air required) can be difficult to determine. Because of the potential for excessive temperatures and fire, it is important to be able to monitor primary data (waste temperature, O2, CH4, CO2 readings) within the landfill and to modify air and liquid application rates to ensure waste mass temperature remain within operating ranges. This can be challenging in such large systems.

To address these challenges, there have been two recent advances, primarily the collection of heat and energy data, and modeling. First, a comprehensive waste and landfill characterization program should consider the aspects listed in Table 2. In addition to leachate, gas, and waste characterization, the geotechnical properties of the waste related to heat transfer should be determined. Finally, a mass/heat balance should be prepared, based on the amount of waste and percentage biodegradable waste values to determine specific air injection and water addition rates. Important data for this task include, but are not limited to, the volume of waste, moisture content of the refuse, and percentage of degradable solids in the mass/heat balance. Upper and lower confidence limits should be used for the moisture content, percentage of degradable solids, and the associated range of waste volumes to determine the range of possible conditions that an aerobic system will operate under. Reasonable estimates for the specific heat of solids, water, and dry gas should also be used, as well as an estimate of the heat of combustion for the waste. The relative humidity of the exhaust air stream in most cases is assumed to be 100 percent, and the average temperature of the exhaust air stream is assumed to be 60 degrees Centigrade (140 degrees Fahrenheit) a temperature characteristic of a well-operating aerobic system in most climates. Average daily relative humidity and average daily temperature values for the general landfill area should also be considered. As part of this exercise, the following aspects should be determined or estimated:

Primary Heat Removal Processes

- Vaporization Of Water
- Advective Transport Of Heat In Air Flow
- Thermal Properties Of Wet Air
- Vaporization Of Water
- Energy Balance

Energy Balance

- % Of Total Energy
- Applied Water
- Heat In
- Injected Air
- Extracted Air
- Heat Associated With Water Vaporization
- Heat Released During Aerobic Degradation
- Initial Heat Initial Heat Of Refuse
- Final Heat Of Refuse

Other Observations:

- Heat Flow, Heat Generation, And Oxygen Transport Are Coupled, Non-Linear Processes
- Venting well design

Table 2. List of Key Parameters of Heat and Energy Balance within an Aerobic Bioreactor

To more accurately estimate air flow rates and pressure responses in the landfill, air pumping tests should be conducted. Available to the designer are computer programs that use the measured flow rates and pressure responses as input, and solves for pneumatic properties using an automated parameter estimation routine. These data are analyzed primarily for horizontal gas permeability and porosity, but estimates of vertical gas permeability can also be obtained. Further, data can be analyzed using a one dimensional numerical gas flow model. The measured atmospheric pressure is used as a boundary condition for the ground surface. The vertical permeability of cover, and refuse, along with the LFG generation rate, are then varied until an acceptable match between measured and simulated subsurface pressures are obtained. Gas porosity values used in the numerical model are based on the pump test analyses.

Although there is a representative amount of bench-scale data, gaseous emissions from full-scale aerobic landfills are being further investigated as they may impact regulatory compliance. Although there is little, if any, evidence on the production of nitrous oxide from full-scale systems, future aerobic applications should include some degree of investigation for this gas. Further, although studies have shown a reduction in vapor-phase volatile organics that are produced under anaerobic conditions, a database of such reductions should be developed before routine permitting of such systems can occur. Although leachate pH has shown to become more neutral under aerobic treatment, thus possibly reducing the dissolution of certain metals into the leachate, the fate of metals when operating the landfill aerobically may require further study. Clogging as a result of a build-up of carbon dioxide has been observed when air enters the leachate collection system (or from changing the in-situ conditions from anaerobic to aerobic).

Another potential challenge to aerobic landfilling is cost, as economics can drive operational decisions. However, with the exception of blowers, overall capital and installation costs for anaerobic and aerobic systems can be similar in some cases, especially when one considers the cost of labor, materials, and risks associated with multiple trenching and piping placements during filling of the cell (anaerobic bioreactor). Further, if low-flow aerobic designs are desired, less blower and pump capacity may be required. Although operating costs for aerobic systems (mostly associated with the electricity required) can be higher than anaerobic ones, the multiple benefits that can be derived (i.e. reduce methane and leachate management costs, more quality leachate, less odors) could offset these costs. Although, it is unlikely that airspace recovery alone will economically justify aerating landfills, a more rapid waste degradation/stabilization strategy via aerobic landfilling could expedite landfill cell reuse (the sustainable landfill and ultimate in "airspace recovery") more cost-effectively than an anaerobic degradation approach.

There are many technical and non-technical factors that can influence aerobic landfill design and operational (e.g. different blower speeds, waste tonnage, biodegradable fraction, liquid application rate, operating cycles, regulatory considerations). As such, this fosters wide ranges in cost and can change the economic perspective of landfilling. For example, the Williamson County aerobic landfill has cost over $2 million since 2000. With respect to over 68,000 tons of waste that is being treated, the unit cost per ton is approximately $29, a significant amount when compared to other landfill costs. However, the landfill owner has saved over $2 million in leachate treatment costs, does not require LFG or odor control nor flaring system, stands to save over $1 million in closure capping and post-closure monitoring (due to reduced risk), and potentially will avoid millions of more dollars in likely groundwater remediation. At present, there are discussions to redevelop this landfill. If so, such development would not only generate additional revenues related to the sale of the property but also related to an increase in tax monies. It can be readily assumed that these combined savings and additional revenues (and in consideration of using present value analysis) could be well worth over $10 million. As such, the unit "benefit per ton" would be approximately $150, a five-to-one ratio. Further, as the aerobic bioreactor helps "return" the property to a more valuable use, these benefits could be realized much sooner than other approaches.

5. THE FUTURE OF AEROBIC LANDFILLS IN THE US

The future of anaerobic and aerobic bioreactors lay primarily in the hands of landfill owners, scientists, and regulators. However, they must be view as unique systems and be designed for site-specific conditions and regulations. In 2002, the US Environmental Protection Agency (EPA) promulgated Research, Demonstration, and Development regulations to help spur further research into approaches, including anaerobic and aerobic bioreactors. Further, the EPA recognizes that aerobic landfills "*increase the rate of decomposition, reduce the emissions of harmful and odorous trace gases, and improve the quality of leachate. These advantages are significant in terms of pollution reduction and the reclamation of landfill sites."* (EPA, 1993) With this in mind, landfills can be rapidly degraded, thus protecting the environment more effectively. In addition, smaller, more economical landfills cells can be built and then treated by an AL process. As a result, operating and closure costs can be reduced. Further, worldwide data supports EPA's view on the AL as a methane control strategy, citing: "*landfills can be designed to be aerobic so that less methane is produced…. More advanced designs…have achieved reductions of over 80 percent."* (EPA, 1993) With this in mind, regulators can encourage research and landfill owners to more rapidly reduce the inevitable risks from landfills, thereby savings millions of dollars of potential cleanup costs and health-related remedies.

However, there are technical and non-technical factors that may influence the future of aerobic bioreactors. These include, but are not limited to;

- Of the nations 2,500+ operating landfills, about 600 are candidate sites for LFGTE, many of which could desire anaerobic bioreactors to produce more LFG. Thus, there are numerous sites that may require LFG management. As flaring may not be desired in some cases, and as there are also an estimated 50,000+ unlined or closed landfills that also may require LFG control and/or remediation, there is an opportunity for growth of aerobic landfill projects;
- Wastewater treatment plants (WWTPs) are facing more stringent treatment requirements. As the aerobic not only can reduce the flow to these plants, but also improve the leachate quality, and, thus, reduce treatment demand;
- As new landfill permits are becoming rare and public concerns increase, approaches that maximize airspace while protecting the environment are of high interest. As more aerobic landfill projects are completed, and the remaining materials tested and analyzed for possible reuse or recycling, there may be an increased demand for more "sustainable landfills." Thus, the rate of "cell reuse" must be attractive economically.
- In the preamble to National Emission Standards for Hazardous Air Pollutants (NESHAP) regulation of bioreactor landfill, EPA concluded that as there is little data available to include aerobic landfills in this regulation. Further, it expected relatively few bioreactor landfills to be operated aerobically. However, EPA is monitoring the growth of new projects, as reported herein, and plans to review the generated data as they become available to determine their impact on NESHAP.
- Although, it may be too early to establish current trends, it appears that this technology has application in the US at small landfills where methane collection and beneficial use is not economical, for rapid remediation of older landfill sites for site redevelopment, where rapid initiation of waste degradation is desirable for airspace recovery, and where the potential for aerating areas of the landfill to create an economically attractive option for leachate treatment.
- Although higher operating costs may be a barrier to some aerobic projects, future costs, as seen with many emerging technologies, may shrink as advancements and improvements in the technology's design, construction, operation, and monitoring increase.

Although many landfills owners can obtain additional benefits by adding air, long-term aeration may not be practical or be sensitive to project economics. To justify the economics of a long-term aerobic landfill project, either 1) air would need to be injected a very low rates (e.g. the 18-year old Donlands site) or 2) the benefits (or savings) of such an approach would need to outweigh the costs. However, the goal of aerobic landfills is to reach the endpoint of waste decay in a relatively shorter time, as compared to other bioreactor approaches. Further, rapid waste stabilization, in some cases, may create new opportunities for cell reuse.

In some cases, varying the operation of an aerobic landfill can provide benefits. For example, the aerobic landfill can be used periodically, either to initiate biological reactions early in the landfill life, or near the end. Further, the approach can be used to remediate old landfills, or later in the life of the landfill, to polish leachate quality and/or reduce methane gas volumes which have fallen below "economically justifiable" production levels. These types of landfills are called hybrids and involve sequencing of anaerobic and aerobic conditions. Two types of these aerobic/anaerobic systems have been explored: short term cycling of air injection into the landfill and sequencing of aerobic and anaerobic conditions.

Cycling of air consists of alternating in-situ aerobic and anaerobic conditions that are repeated throughout the life-cycle of the landfill, sequencing air injection into the landfill via an initial aerobic phase, and followed by a final anaerobic phase. Because there are many advantages associated with both aerobic and anaerobic degradation processes, researchers see combining the processes as one way to maximize landfill gas production and possibly remove nitrogen from landfills.

There are some components in both the waste and leachate that are recalcitrant in anaerobic conditions, but degradable in aerobic environments, such as lignins and aromatic compounds. Utilizing one of these hybrid techniques may allow for the leachate and/or waste to be treated more completely (Berge, 2001; Reinhart et al., 2002). Operating a bioreactor landfill as a hybrid system may serve to combine several nitrogen transformation and removal processes, such as nitrification and denitrification, potentially resulting in complete in-situ removal of nitrogen from landfills.

In a sequencing air-injection system, waste is placed in lifts. The first lift is aerated for a period of time; when the second lift is placed, aeration of the first layer stops and aeration of the second layer commences. Leachate is continuously recirculated. This process continues until the landfill is filled (Hater and Green, 2001). It is hypothesized that this system acts to speed typical anaerobic degradation processes, specifically the onset of methanogenesis. By initially aerobically degrading the waste, the temperature of the waste is increased and the extent of the acidogenic phase is reduced, therefore allowing for the early onset of methanogenesis. Hybrid Aerobic-Anaerobic Landfill Bioreactor (AALB) cells were built at the Outer Loop Landfill near Louisville, KY in 2001 (Hater et al., 2005). Two 2.45-ha test cells were operated in parallel with similarly sized control cells. Each cell was isolated by clay and shredded tires. The cells were constructed by placing 4.5-m lifts of waste, adding water to increase moisture content, and placing a horizontal perforated piping system for air and liquid injection. Waste continued to be added in 4.5-m lifts. By 2005, the cells had reached 21 m in depth. The pipes were perforated within 17 m of the landfill side slope. Air is injected for a period of 30 to 60 days (60 m^3/min) to each lift to rapidly degrade the waste. Temperature was used to control airflow; requiring a cutoff of air with an increase of 7^{o}C in 24 hours or upon reaching 71^{o}C. However, a maximum temperature of 38.8^{o}C has been reported to date. Preliminary reports show enhanced waste degradation for the AALB as compared to the control anaerobic cells measured by a decrease in cellulose to lignin ratios and Biochemical Methane Potential (Green et al., 2005). Density has increased by 14-27%.

When using aeration for in-situ leachate and waste treatment, a smaller portion of the landfill could be aerated (potentially only a 200 m^2 area), resulting in lower operational costs and capital equipment requirements. Based on costs of treating leachate both off-site ($0.09 – 0.42/gal) and on-site ($0.004 – 0.24/gal), aerating a portion of landfill to use as a dedicated leachate treatment zone can be an economically attractive option. Parameters such as BOD, COD and ammonia-nitrogen could be significantly reduced in relatively quick time periods. Berge (2006) found the cost of treating ammonia-nitrogen in-situ (if aerating a 200-m^2 area) would range from $0.0019 - 0.045/gal, well below the off-site treatment costs and on the low end of the on-site treatment costs. Potentially, after in-situ aerobic treatment of the leachate, the leachate could be discharged directly to a receiving body of water or stream. Additionally, any risk associated with leachate leaking into the groundwater would be minimized, as would any risk associated with transportation of the leachate.

There are many technical and non-technical factors that can influence aerobic landfill design and operation. As such, further research and applications should be conducted to obtain further understanding of the operation of these type systems and to improve performance. In addition, each type of bioreactor should be viewed as unique biological systems and take into account the wide variability of site conditions, waste characteristics, landfill construction, and performance goals. In this way, the owner can best select the most appropriate bioreactor approach.

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