THE ROLE OF LANDFILLS IN US SUSTAINABLE WASTE MANAGEMENT

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ABSTRACT

Sustainable solid waste management involves socially-acceptable solutions that minimize environmental impacts and cost, and incorporate waste minimization, recycling, treatment, and landfill disposal practices. This paper discusses the role of the landfill in sustainable waste management, including sustainable operation and design to control emissions, greenhouse gas issues, waste diversion, gas to energy opportunities, and a new concept, pump and treat aerobic flushing, for sustainable landfill operation to completion. Through these practices, landfills can promote safe waste disposal. Greenhouse gas emission offsets can be achieved through the collection and beneficial use of methane and carbon dioxide, in addition to the storage of calcite carbon. Landfill-gas-to-energy projects provide an opportunity for compensation for reduced gas emissions. However, it appears that reduction of emissions beyond current practice may not be cost effective because of the high cost of fugitive emissions avoidance.

INTRODUCTION

Sustainable solid waste management involves socially-acceptable solutions that minimize environmental impacts and cost. There is a generally accepted hierarchy to sustainable waste management that involves waste minimization, recycling, treatment, and landfill disposal. Landfill disposal of non-recoverable and non-recyclable waste is inevitable and, in countries with large land resources, relatively well accepted. In developing countries, landfills offer a low cost option for waste management and a potential revenue source through sale of energy and carbon credits associated with landfill gas (LFG) collection and destruction.

Landfills should be designed and operated to reach a sustainability goal. Ideally, the end result of operating a sustainable landfill will be a stable, reusable land area which is in equilibrium with the environment within one generation. An example of sustainable landfilling is the current European Union Directive, which achieves this concept by permitting landfill disposal of predominately inorganic waste only, through extensive mechanical, biological pretreatment. Also, in the State of Wisconsin, a landfill organic stability plan rule was enacted in 2006 with the objectives that landfills reach (1) an organically stable state with minimal LFG production, (2) low-organic-component landfill leachate, and (3) stable landfill elevations (complete landfill settlement). Landfill operation to accelerate the stabilization of waste approaches sustainable landfilling (bioreactor landfilling) at considerably lower cost than mechanical or biological waste pretreatment followed by landfilling. In some parts of the world, however, sustainable landfilling may not yet be possible due to economic constraints. This paper discusses the role of the landfill in sustainable waste management, including operation and design to control emissions, greenhouse gas issues, gas to energy opportunities, and a new concept (pump and treat aerobic flushing) for landfill operation to completion.

WASTE DIVERSION

The overall interest in waste diversion has been increasing due to societal movement towards sustainability. Waste diversion would increase material and energy recovery; decreasing the amount of unnecessary waste and conserving natural resources. Diversion goals in the US currently range from 25% up to 100%, or “zero waste.” Zero waste is defined as diverting 100% of the waste from a landfill, and primarily relies on combustion of waste with energy recovery. Several US communities have implemented a zero waste program, for example in 2007 San Jose, California established a goal of 100% diversion from landfills by 2022. It should be noted that zero waste is an aspirational goal; there will always be a need to dispose of waste that cannot be incinerated or that remains after incineration. While some residuals generated from solid waste combustion processes can be beneficially used (e.g., daily landfill cover or in road construction), there are limitations on alternatives to landfills.

Diversion of solid waste will increase the life of landfills, but can reduce production of gas that can otherwise be used as a renewable energy source. For example, the diversion of 33% of the MSW generated in the US in 2006, reduced GHG emissions by 50 million metric tons of carbon equivalent (MTCE). This reduction equates to the GHG emissions from 39 million cars (USEPA, March 2008). However, studies show that diverting rapidly decomposing MSW components, mainly food waste, would significantly reduce LFG production but would have minimal effect on the energy production due to the fact that LFG from such components would be generated prior to initiation of LFG collection in most cases (Amini, 2011).

THE BIOREACTOR LANDFILL

The bioreactor landfill is an important component of current sustainable waste management practices. Much research has
been conducted to create an efficient bioreactor landfill system that can significantly reduce pollution potential of municipal solid waste (MSW) within a decade (Reinhart and Townsend, 1998; Reinhart et al., 2002). The benefits of bioreactor landfills have been well documented by a variety of researchers and include enhanced and accelerated waste stabilization, greater and more reliable gas production, improved leachate quality, and more rapid landfill settlement. The most effective (but not the only) element of bioreactor operation is moisture control through liquid injection. Liquid is commonly injected using permeable blankets, tankers at the working face, surface ponds, spray or drip irrigation, horizontal trenches, and/or vertical wells.

**LANDFILL EMISSIONS**

Emissions from landfills (i.e. methane and carbon dioxide) can be controlled to minimize environmental impact while waste degradation and bio-stabilization of the waste occurs. These processes and system components include construction and maintenance of an effective bottom liner and leachate collection system, optimization of environmental conditions to promote waste stabilization through controlled liquid addition, in-situ treatment of leachate constituents, efficient collection of LFG, placement of an active biocover to control fugitive LFG emissions through methane oxidation, and beneficial utilization of methane generated during waste degradation.

**Leachate.** A liner system is generally required to prevent migration of leachate from the landfill and to facilitate leachate removal. To minimize risk of contamination, a liner consists of multiple layers composed of natural material (usually clay) and/or geomembranes. Landfills may be designed with single, composite, or double liners depending on the applicable regulations. A single liner provides only a clay or geomembrane layer while a composite liner consists of two layers - a clay material overlain by a geomembrane. The two layers of a composite liner are in intimate contact to maximize moisture restriction. A double liner may be either two single liners or two composite liners (or even one of each) separated by a leak detection system - a series of pipes placed between the liners to collect and monitor any leachate leaking through the upper liner. Clearly, the more layers that are included, the more protective the liner system will be, however costs will increase dramatically. Leachate is rapidly directed to low points at the bottom of the landfill through the use of an efficient drainage layer composed of sand, gravel, or a geosynthetic net. Perforated pipes are placed at the low points to collect leachate. These pipes are sloped to allow the moisture to move out of the landfill. A study of 187 double-lined landfill US cells concluded that these liners are capable of 90 to 99% hydraulic efficiencies with leakages often less than 2 liters/ha/day (Bonaparte et al., 2002).

**Gas.** Waste is covered at the end of each working day with soil or an alternative daily cover material such as textiles, geomembrane, carpet, foam, or other proprietary materials. The landfill sides are sloped to facilitate maintenance and to maximize slope stability. Once the landfill reaches design height, a final cap is constructed to minimize the infiltration of rainwater, minimize waste dispersal, accommodate settling, and facilitate long-term maintenance. The cap may consist (from top to bottom) of vegetation and supporting soil, a filter and drainage layer, a hydraulic barrier, foundation for the hydraulic barrier, and a gas control layer. Because of the prevailing anaerobic conditions within a biologically active landfill, these sites produce large quantities of gas composed of methane, carbon dioxide, water, and various trace components such as ammonia, sulfide, and non-methane volatile organic carbon compounds (VOCs). Reported LFG production rates vary from 0.12 to 0.41 m³/kg dry waste (Pohland and Harper, 1985). LFG is generally controlled by installing vertical or horizontal wells within the landfill. These wells are either vented to the atmosphere (if gas migration control is the primary intent of the system) or connected to a central blower system that pulls gas to a flare or treatment process.

**Carbon Storage**

Anaerobic conditions normally prevail in landfills which are not conducive to the decomposition of lignins or to cellulolic material protected by lignins. Consequently, much of the wood and paper products, which are primarily lignin and cellulose, will remain in the landfill for very long periods of time. Thus, while landfills tend to contribute large amounts of greenhouse gases, to some extent they offset these emissions through carbon storage. Landfilled paper, yard trimmings, and food wastes accounted for 1.2 percent of the total US carbon sequestration in 2009 (USEPA, 2011).

**LANDFILL-GAS-TO-ENERGY PROJECTS**

LFG can pose an environmental threat due to the presence of greenhouse gases, odorous or potentially toxic VOCs, and the explosive nature of methane. However, the gas has high energy content and can be captured for power, steam, or heat generation. Treatment of the gas prior to beneficial use may include condensation of water and some of the organic acids and/or the removal of sulfide, particulates, heavy metals, VOCs, and carbon dioxide. Collection and destruction of the meth-
ane in LFG allows Annex I countries to meet emission targets by using credits purchased through a Clean Development Mechanism under the Kyoto Protocol. The cost of reducing greenhouse gas emissions in developing countries is a fraction of that in developed countries. Obviously, when a project is coupled with energy production the benefits are even greater. Carbon emission trading has created a strong worldwide market. The value of the European carbon trading market was about USD 95 billion in 2008, while the US voluntary carbon trading market value was over USD 0.7 billion in 2008 (Hamilton et al., 2009) However, following the economic recession the estimated global carbon market value dropped from USD 118 billion in 2008 to USD 84 billion in 2009 (Carbon Positive, 2009).

In the US there are over 540 (as of December 2010) LFG recovery projects capturing and beneficially using some 9.4 billion m$^3$ of LFG annually. The energy produced by these projects is equivalent to heating over 2.1 million homes. The reduced emissions from these projects are over 75 million metric tonnes of carbon equivalents per year (US EPA LMOP, 2011). The US Environmental Protection Agency created the Landfill Methane Outreach Program (LMOP) and, internationally, the Methane to Markets Partnership (M2M) to encourage LFG recovery and beneficial use. Some of the uses of LFG are described below.

**Boilers and Other Direct Combustion Applications.** Direct combustion of LFG is by far the cheapest and easiest option. Direct use of LFG to replace or supplement coal, oil, propane, and natural gas has been successfully demonstrated. Applications include boiler firing, space heating, cement and brick kilns, sludge drying, and leachate drying and incineration. In most cases, gas cleanup consists of little more than condensate removal.

**Vehicle Fuel.** A market for LFG as a vehicle fuel exists if the gas is upgraded to natural gas quality. Vehicles can be modified for operating on some form of natural gas. Refueling stations are available and are equipped for dispensing natural gas. The technology is established for liquid natural gas (LNG) and compressed natural gas (CNG).

**Conversion to Synthetic Fuels/Chemicals.** It is technically possible, even if not economically feasible, to produce synthetic fuels and chemicals from LFG. The technologies include hydrocarbon production by the Fischer-Tropsch process and methanol synthesis by high pressure chemical catalysis and partial biological oxidation. Synthesis gas-based chemical processes for acetic acid and other compounds are also available. These technologies were developed for large-scale production of synfuels using coal gas feed stocks. Production ventures were costly and their products were expensive.

**Electrical Power Generation.** Generation of electricity, using reciprocating internal combustion and gas turbine engines, is by far the most common LFG-to-energy application. A number of proven technologies with a range of economics of scale easily adapted to LFG, highly developed and distributed transmission infrastructure, and a virtually limitless market make LFG-to-electricity one of the easiest and most profitable alternatives.

**Electrical Power Generation (Fuel Cells).** Until recently, the well-established technology of fuel cells was subject to unfavorable economics when using LFG. Fuel cells are electrochemical batteries utilizing molten carbonate or phosphoric acid fueled by coal, petroleum, natural gas, or other such hydrocarbon feedstocks. Hydrogen from the converted fuel combines with oxygen to produce electricity.

**Purification to Pipeline Quality Natural Gas.** There are major differences between LFG and natural gas in composition and energy content. LFG has a lower BTU content, combusts at a lower temperature, is more corrosive, and contains much greater concentrations of undesirable gases (CO$_2$, O$_2$, N$_2$) and harmful halocarbons than pipeline-quality natural gas. Diligent extraction and stringent cleanup is therefore necessary to render LFG devoid of all components except methane. The required gas cleanup, an expensive and complex process for other alternatives, includes nearly complete CO$_2$ removal.

**Conversion to Hydrogen Gas.** Hydrogen can be produced by catalytic processing of LFG with minimal environmental impact. Hydrogen gas could be used locally by a variety of end-users (e.g., in transportation or for on-site generation of heat and/or electricity using energy efficient fuel cells). The Florida Solar Energy Center at the University of Central Florida (Orlando, FL, US) has proposed this concept based on direct (i.e., without preliminary recovery of methane) reforming of LFG to synthesis gas (or syngas) via CO$_2$-reforming of methane (often called, “dry” reforming) according to the equation (Muradov et al., 2008):

$$
\text{CH}_4 + \text{CO}_2 \rightarrow 2\text{H}_2 + 2\text{CO}
$$

$$
H^\circ_{298} = 247 \text{ kJ/mol}
$$

This is an endothermic reaction that operates at 850-950°C (i.e., the same temperature range as commercial steam methane reforming, SMR, process) and produces syngas with the H$_2$:CO ratio of approximately 1:1. Most of the H$_2$S and other harmful contaminants have to be removed from LFG before the reforming stage in order to prolong the life of the catalysts used in the process. The purified CH$_4$:CO$_2$ mixture enters a catalytic reformer, where it is processed into syngas. The syngas is further processed in the CO-shift reactor to H$_2$:CO$_2$ mixture according to the reaction (2):

$$
\text{CO} + (\text{H}_2\text{O}) \rightarrow \text{H}_2 + \text{CO}_2
$$

$$
H^\circ_{298} = -41.5 \text{ kJ/mol}
$$

At the final gas separation stage of the process, hydrogen gas with 99.999 vol. % purity is recovered from H$_2$:CO$_2$ mixture using a pressure swing adsorption (PSA) unit. A pilot-scale unit with the capacity of 5 kW of hydrogen gas was designed, fabricated and tested (Muradov et al., 2008).

**PUMP AND TREAT AEROBIC FLUSHING BIOREACTOR LANDFILL: A NEW CONCEPT**

After the landfill has been operated as a bioreactor for a period of time and the anaerobically biologically degradable organic compounds are removed, the leachate may contain organic contaminants and refractory organic by-products that threaten the environment and human health. Once gas production declines to a point where it is no longer economi-
cal or feasible to generate electricity, the objectives of landfill operation change to final stabilization of waste. At this point, consideration should be given to shifting to an aerobic mode of treatment. In addition, bioreactor landfill operation tends to yield high ammonia-nitrogen concentrations. Ammonia-nitrogen concentrations tend to increase beyond concentrations found in leachate from conventional landfills because recirculating leachate under anaerobic conditions increases the rate of ammonification and provides no major biological pathway for ammonia removal (Berge et al., 2006).

In order to reduce landfilling long-term liability and environmental impact, in the US post-closure care (PCC) of landfills is now required for 30 years, however this time period may be inadequate and PCC may actually be needed indefinitely. In some cases, removal of both remaining organic contaminants and ammonia-nitrogen must be accomplished before landfill post-closure periods can end. Removal of these constituents may require a series of costly biological, chemical and physical processes either at a local treatment plant or on-site facilities. To minimize PCC following biological anaerobic digestion of waste in a bioreactor landfill, a completion phase is proposed during which remaining contaminants such as leachable ammonia and organic and inorganic contaminants are treated and/or removed from the landfill through a combination of in-situ biological and ex-situ oxidation processes (Batarseh et al., 2010).

This method uses leachate indigenous to the landfill cell as the flushing media as opposed to using clean water. As leachate is flushed, it is chemically treated outside the cell, and subsequently pumped back into the cell to transport more of the releasable carbon, as seen in Figure 1. Additional carbon that resisted anaerobic degradation could be removed from the landfill cell by aerobic biodegradation if air is injected into landfill. With such a process, the ultimate end products within a landfill are essentially humic matter and inert inorganics. Recent batch and modeling studies (Reinhart et al., 2006) have preliminarily demonstrated the economic and technical feasibility of a concept called a Pump and Treat Aerobic Flushing

**Bioreactor Landfill** (PTAFBL), estimated to add approximately $23 per ton landfilled (Batarseh et al., 2010). This process is proposed to provide sustainable landfilling by removing releasable carbon, dissolved solids, and ammonia nitrogen at the end of a MSW landfill life as shown in Figure 1.

This concept has application to both operating landfills and to closed sites, which number in the US in the many thousands. Ideally the end result of operating a landfill in this fashion will be a stable, reusable land area. This suggested method is recommended to be applied as a post-bioreactor landfill treatment step with the objective of producing stable solid waste cells, with the potential to rapidly recover the landfill site for redevelopment (i.e. recreational park, nature reserve, golf course, or industrial sites).

**FUKUOKA SEMI-AEROBIC LANDFILL METHOD**

As an alternative means to fully stabilizing landfilled waste, particularly in developing countries, a semi-aerobic landfill can be considered. The Fukuoka Semi-Aerobic Landfill Method (Chong et al., 2005) is a proven technology in Japan that has been proposed or constructed around the world because of potential economic benefits. Aerobic treatment of waste could have multiple advantages, including biological treatment of waste and leachate constituents that are recalcitrant under anaerobic conditions (such as ammonia) while controlling methane production. Low pressure aeration has been used in Germany to accelerate aerobic stabilization (Heyer et al., 2005). Addition of air can be accomplished passively according to the Fukuoka Method by removing gas extraction wells/blankets from the extraction system and promoting gas convection within the waste. Aerobic treatment of the waste results in a temperature elevation which promotes convection of air upward from the leachate collection system, through the waste, and out the gas vents. The leachate collection system must be constructed of highly permeable material to promote passive aeration, such as river rock.

**CONCLUSIONS**

While many landfills have historically created pollution through improper siting, design, and/or operation, the potential for sustainable landfilling does exist. Landfilling of waste is currently inevitable and modern landfill practices can promote safe land disposal. Leachate can be safely collected and treated, reducing the potential for ground and surface water contamination. Methane can be either collected and beneficially used or oxidized in soil covers; carbon dioxide can be sequestered cryogenically or sold for commercial use, and recalcitrant carbon can be stored in the landfill, all resulting in greenhouse gas emission offsets. However, significant reduction of gas emissions beyond common practice today, does not appear to be cost-effective because of the cost of high level of gas collection.
REFERENCES


