WATER REQUIREMENT ESTIMATES FOR AN AEROBIC BIOREACTOR LANDFILL IN CHINA

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SUMMARY: This paper provides an overview of step-by-step calculations, based on the stoichiometry of biotic respiration reactions, to estimate values for water inputs/production and consumption/uptake for an aerobic bioreactor landfill project in China located in a semi-arid climate. Estimates are made in two parts: (1) the initial amount of water required to increase the waste moisture content to a preferred range of at least 40 percent and (2) the amount of water required for hydrolysis and biologically-mediated oxidation reactions to sustain microbial activities during operations. This case study example is representative of retrofitting bioreactor concepts in an engineered landfill. The results indicate that for a 14-hectare landfill, some 150 million liters of water will be consumed initially for an aerobic bioreactor process, meaning a significant water source is required. Also, once the process is underway, the aerobic landfill is estimated to consume an additional 220 million liters of water to sustain the aerobic process.

1. INTRODUCTION

As early as the late 1990s, aerobic biodegradation processes (aerobic bioreactor) were developed using the landfill itself as a treatment bed (similar to a large closed vessel), to promote a more rapid and effective treatment of waste and leachate. This biodegradation process involves adding air, moisture, and other nutrients uniformly to the waste mass on a large scale similar to waste composting, but without mixing or windrowing of the waste. Various benefits occur, including reduced concentrations of certain organic compounds typically found in wastewater and leachate (Read, 2001).

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Management of traditional anaerobic landfills assumes that waste degradation is slow and that methane gas will be produced in concentrations greater than 50 percent by volume of the total landfill gases (LFG) (Doorn, 1995). Active aerobic biodegradation processes (such as composting); however, have demonstrated that the biodegradable portion of municipal solid waste (MSW) can be stabilized in a significantly shorter time frame (as compared to anaerobic conditions) and that (due to the increased availability of injected oxygen), methane production can be greatly reduced (Stessel, 1992). Further, by recirculating the leachate back into the waste (assuming there is a suitable leachate collection system) and, at the same time, injecting air into the waste, the facultative and respiring bacteria inherent to the waste convert the biodegradable mass of the waste and other organic compounds to mostly carbon dioxide and water (instead of methane), with a safe, degraded humus remaining (Hazen, 2000). Because aerobic biodegradation also treats liquids by reducing contaminant concentrations, the need for subsequent landfill leachate treatment is reduced.

Water production and consumption data have been collected from several aerobic landfill projects for over a decade. While more research is still needed, it is reasonable to hypothesize the production and consumption of liquids in an aerobic landfill by a review of the basic stoichiometry of composting and related mechanical/thermal processes, and then comparing the results to those obtained in the field. This paper presents the methodology of estimating quantitatively the water inputs/production and water consumption/uptakes in aerobic bioreactor landfill environments.

2. FRAMEWORK OF THE STUDY

The aerobic landfill process is essentially a biological one that involves the growth and control of microorganisms. The rate of the aerobic process, like the rate of composting, can be affected by many factors. Although composting and aerobic landfilling are conducted using different engineering solutions (windrows versus air injection), the ability to provide oxygen, water, and nutrients to a unit volume of waste (organics) is quite similar. Therefore, large scale composting can serve as a surrogate for aerobic landfilling.

Aerobic landfill systems rely on natural composting through provision of oxygen and moisture to the waste mass, typically accomplished via wells installed into the waste. Typically, aerobic landfill systems can be integrated into the existing landfill infrastructure using the components of the existing LFG collection systems. Aerobic conditions are balanced by adjusting the flow of liquids and air that are injected into the waste mass to keep the waste moist and aerated, and to keep landfill gases (CO_2, CH_4, and O_2) and waste mass temperatures within preferred ranges.

2.1 Stoichiometry

Aerobic degradation of waste can be represented by the following reaction (Tchobanoglous, 1993):

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$$C_aH_bO_cN_d + (4a+b-2c-3d)/4\ O_2 \rightarrow aCO_2 + dNH_3 + (b-3d)/2\ H_2O \quad (1)$$

Where:

$C_aH_bO_cN_d$ = molar composition of the organic waste, or equivalent to: $C_{35}H_{73}O_{30}N$

The use of Equation (1) provides a conservative estimate of the oxygen required as bioconversion to end products is less than 100 percent. This equation was used to estimate water production and demand, oxygen uptake, and nitrogen requirements, as presented below.

The primary goal of the aerobic landfill process is to achieve optimum waste stabilization through aerobic degradation (Hudgins, 2007). This is defined in terms of a stabilized organic matter, decreased concentrations of leachate contaminants, reduced methane production, and waste mass subsidence. Laboratory and field analyses provide the data needed to assess the system's effectiveness on the leachate. Direct measurements of landfill gases are made for methane and non-methane organic compound concentrations. Subsidence of the landfill waste mass is monitored by physical survey. The biodegradation rate is assessed based on oxygen uptake rates, reduction in volatile solids (VS) material, and waste mass temperature measurements. Upon stabilization, the waste can be excavated to examine the degree of aerobic decomposition.

In many cases, the degree of bioconversion can be estimated by calculating the biodegradable fraction of the solid waste using Equation (2) (Chandler, 1980):

$$BF = 0.83 - 0.028\ LC \quad (2)$$

where BF =biodegradable solids fraction expressed on a volatile solids (VS) basis
0.83 = empirical constant
0.028 = empirical constant
LC = lignin content of VS as a percent of dry weight

Biodegradability fractions range from 0.22 for newsprint up to 0.82 for food wastes.

2.2 Targeted Moisture Content

Maximum moisture content for satisfactory aerobic operation varies with the waste materials present. If the waste materials contain considerable amounts of strong fibrous material, the maximum moisture content can be much greater without destroying the structural qualities or causing the material to become soggy, compact, and unable to contain enough air in the interstices. If the waste material has little structural strength when wetted, or if it is granular, like ash and soil, it may be difficult to maintain aerobic conditions.

The targeted moisture content of MSW should typically be at least 40 percent, but may be in a range between 40 to 70 percent. This is important because as the target moisture content is exceeded, the structural strength of the organic matter deteriorates, oxygen movement is inhibited, and the process tends to become anaerobic. As the moisture content decreases below 50 percent, the rate of decomposition decreases rapidly (Hansen, 1995). If the moisture content falls much below 40 percent, many of the organisms will cease to function. Moisture content above 70 percent may cause the waste to go anaerobic, thereby producing foul odors.

3. CHINA CASE STUDY ANALYSIS AND DISCUSSION

The goal of this case study sample calculation is to theoretically derive, based on the stoichiometry of biotic respiration reactions, values for water inputs/production and consumption/uptake. Also, a water balance within the bioreactor system is performed to estimate the amount of extraneous water that should be added to the system throughout the operation. Presented below is a sample calculation of water requirements at an aerobic bioreactor landfill remediation project in China.

3.1 Assumptions

Based on site information and from data collected during site inspections, performance modeling was based on the following field data (2007) and assumptions:

- Landfill subject area: 1.4 million square meters, or 14 hectares (measured);
- Volume of waste: 2 million cubic meters (measured);
- Waste density: 350 kg/m^3 (estimated);
- In-place waste moisture content: 27.66 percent (measured);
- Volatile Solids (VS): 22 percent of Total Solids (measured);
- Biodegradable Fraction of Volatile Solids: 60 percent of VS (measured);
- 15 percent of the waste is Carbon (assumed);
- Preferred ratio of Carbon to Nitrogen: 25 to 1;
- No daily cover used (reported);
- Target treatment period for all VS: 2 years (estimate based on stoichiometry).

Assuming the above waste density (no waste compactors used), the discarded weight of total solids (including moisture) inside the subject waste mass (w) is estimated to be 7.1 E+08 kg. This maximum value for waste weight is used, rather than the adjusted value to account for the anaerobically-biodegraded waste fraction, to assess the maximum water requirements.

3.2 Part 1 - Initial Amount of Water Required Prior to Operations

Based on the waste sample collection in 2007, the average reported in-place moisture content (mc) of the waste in the mound is 27.66 percent (by wet weight). This translates to an estimated dry weight, d, of:

$$mc = 100 \times (w - d)/w \qquad (3)$$

27.66 percent = 100 x [(7.1 E+08 kg - d)/ 7.1 E+08 kg]

Solving for d, d = 5.16 E+08 kg

As observed at previous aerobic remediation projects, the estimated minimum moisture content (mc) required is about 40 percent (average by wet weight, w). Therefore, if we assume that 40 percent wet weight is our optimum goal for peak aerobic/composting performance, the volume of additional water required to bring the waste from completely dry weight up to 40 percent wet weight is:

Solving for w, w = 8.61 E+8 kg

Therefore, the additional water required to bring the moisture content from 27.66 percent, its current moisture content, to 40 percent wet weight is about 1.48 E+08 liters.

3.3 Part 2 - Water Required To Sustain Microbial Activity

Assumptions used in Part 2 calculation are:

- Moisture inputs assume an even distribution within the waste.

- Cellulose/hemicelluloses (carbohydrates) are the primary biodegradable carbon source in solid wastes. If we use 63 percent (CEC, 2003) of the total dry weight as cellulose/hemi-cellulose (0.63 x 5.16 E+08 kg dry weight), then 3.25 E+08 lbs is as cellulose/hemi-cellulose. Yet, from previous projects, waste sample analysis indicated that 15 percent of the waste (wet weight) was carbon. For this study, it is assumed there are 1.07 E+08 kg (0.15 x 7.1 E+08 kg) of carbon present.

- Only cellulose/hemi-cellulose reactions were considered, and the associated water production/consumption, for estimation of the water balance, assuming the more conservative weight of 1.07 E+08 kg of carbon.

- Using this value and the preferred C:N ratio of 25:1, the nitrogen requirement was estimated to be 4.29 E+06 kg. Accordingly, there appears to be an adequate amount of nitrogen available from this theoretical calculation[1]. It was assumed that nitrogen requirements do not affect water production or demand.

- [1] This relationship assumes all of the nitrogen is released (100 percent breakdown of organic compounds) and is available for assimilative use by the microorganisms. However, some of the nitrogen may not be readily available due to the presence of any recalcitrant organic species and the subsequent limits to nitrogen release from these compounds. Also, nitrogen use for assimilative purposes by certain species of microbes may be limited depending on the oxidation state of nitrogen. As a result, based on theoretical and empirical data, there may be no need for nitrogen addition to the aerated bioreactor system. Therefore, water estimates do not consider the effects of nitrogen.

- Vaporized moisture does not condense within the waste mass. However, in field observations, there are liquids present because of factors that may include the percentage of treatment effectiveness resulting, variability of waste, leakage through cover, and presence of groundwater.

Based on stoichiometry ratios for water consumption and production relative to carbon, the following totals were derived from Equation 1:

$$C_{35}H_{73}O_{30}N + 37.5O_2 = 35\ CO_2 + 35H_2O + NH_3 \quad (4)$$

Also, the following assumptions were made:

- Composition of organic fraction (including water) of a composite waste sample is $C_{35}H_{73}O_{30}N$ with 449 kg per mole;
- Composted products have total molar weight of 545 kg per mole
- Volatile solids (VS) = 22 percent of total dry solids;
- Total dry solids = 5.18 E+08 kg;
- Total carbon = 1.07 E+08 kg;
- Biodegradable fraction of VS = 60 percent of VS.

3.3.1 Water Consumption (x_b) Via Biotic Reactions

Given that cellulose/ hemi-cellulose (carbohydrates) reactions utilize 4 moles of water per 6 moles of carbon consumed, then the water consumption via hydrolysis/biologically "mediated" oxidation reactions can be calculated as follow:

$$\frac{(4 \times 18)\ \text{kg/mole}\ (H_20)}{(6 \times 12)\ \text{kg/mole (Carbon)}} = \frac{x_b\ \text{kg}\ H_20}{1.07\ \text{E+08 kg of Carbon}} \quad (5)$$

x_b = 1.07 E+08 kg of water, or
= 1.07 E+08 liters of water **consumed.**

3.3.2 Water Production (x_h) Via Biotic Reactions

From the biotic stoichiometry of oxygen requirements, 12.5 moles of water are produced for every mole of organic compound oxidized. Each mole of organic compound found through analysis will contain 12.5 moles of carbon. Therefore, the water production via hydrolysis/biologically "mediated" oxidation reactions can be calculated as:

$$\frac{(12.5 \times 18)\ \text{kg/mole}\ (H_20)}{(12.5 \times 12)\ \text{kg/mole (Carbon)}} = \frac{x_h\ \text{kg}\ H_20}{1.07\ \text{E+08 kg of Carbon}} \quad (6)$$

x_h = 1.61 E+08 kg water, or
= 1.61 E+08 liters of water **produced.**

3.3.3 Water Removal Due to Vaporization

The following assumptions were made:

- The weight of air is approximately 1.137 kg per cubic meter;
- The average inflow air temperature is 37.8 deg *C,* of which approximately 21 percent by mass is O_2. Moisture in the inflow air is ignored to simplify the calculation but it can be important for some arid sites; and,
- The volume of water vaporized and carried via advection with the exhaust air stream is approximately 0.00025 liters per second of water/ liters per second airflow. (CEC, 2003)

Based on Equation 4, a theoretical oxygen demand is calculated to be 0.55 kg O_2 for each kg of organics to convert. Therefore, since there is a total of 1.07 E+08 kg of biodegradable organics to convert, 0.55 x 1.07 E+08 kg or 0.59 E+08 kg of O_2 is needed to be delivered to the system. This is then converted to 55.22 E+10 cubic liters at 100 percent conversion efficiency of O_2 or approximately 8,750 L/s for two years continuous operation. At 50 percent conversion efficiency of O_2, the air required would be 17,500 L/s for two years continuous operation.

Based on the above oxygen requirements at 50 percent conversion efficiency of O_2, the amount of water vapor removed from the system, assuming the vapor is allowed to fully vent to the atmosphere through the vent wells or be extracted via vacuum is:

17,500 L/s x (0.00025 L/s water/ L/s airflow) = 4.38 L/s water content within air flow

Over two years, the total volume of water removed is calculated as 2.74 E+08 liters.

3.3.4 Water Input Due To Infiltration of Precipitation

Using “The Hydraulic Evaluation of Landfill Performance” (HELP) model developed by the U.S. Environmental Protection Agency, water input (i.e., infiltration of precipitation) was calculated as insignificant compared to other volumes. This is due to low rainfall at the arid site and a low permeability clay cover cap (i.e., hydraulic conductivity less than 5×10^{-6} cm/sec). Rainfall or snow melt are presumed to flow through surface water controls and then mainly as surface run-off. The total surface infiltration (calculated at about 5.3 mm per year) over the first two years is estimated at less than 760,000 liters.

3.4 Water Balance Summary

A summary of water input requirements and water consumption for two years of operation is given in Table 1.

Table 1. Water Balance Estimates

Phase	Water Inputs/ Production (million liters)	Water Consumption (million liters)	Net Volume Required (million liters)
Part 1 (before operation)	148	none	148
Part 2 (during operation)			220
- precipitation/infiltration	<0.76		
-hydrolysis/reactions	161	107	
-vapor/advection		274	

4. CONCLUSIONS

Moisture requirements were estimated in two parts for the operation of an aerobic bioreactor landfill. The first part was the initial amount of water needed to increase the waste moisture content to a preferred operational range. The second part was for the amount of water required for hydrolysis and biologically-mediated oxidation to sustain microbial activities during operations. The results indicate that for a 14-hectare landfill, some 150 million liters of water will be consumed initially for an aerobic bioreactor process, meaning a significant water source is required. Also, once the process is underway, the aerobic landfill is estimated to consume an additional 220 million liters of water to sustain the aerobic process in the preferred operational range for moisture content.

Physical and biological processes occurring in most bioconversion systems are not well understood, primarily because of the myriad of possible substrates, climate conditions, geography, landfill geometries, waste characterization, and highly dynamic temperature-moisture conditions. Further, as many landfills in China were constructed with less daily cover (thus lower waste compaction) as compared to engineered landfills within rigorous regulated waste management systems, system performance differences will be expected site to site, country to country. As aerobic landfill operators have managed facilities through composting practices and various trial-and-error methods, the science needs to advance further.

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