BASIS TO SUPPORT THE DEVELOPMENT OF A NEW METHODOLOGY TO DETERMINE AVOIDED GREENHOUSE GAS EMISSIONS FROM IN SITU AEROBIC STABILIZATION OF LANDFILLS

J. PECK*, H. BENTLEY**, AND M. HUDGINS***

** Hydro Geo Chem, Inc., 6340 E. Thomas Road, Ste 224, Scottsdale, AZ 85251*
***Hydro Geo Chem, Inc. 51 W. Wetmore Rd., Ste 101, Tucson, AZ 85705*
****Environmental Control Systems, Inc., 341 Park Ave SW, Aiken, SC 29801*

SUMMARY: The aerobic treatment of solid waste has been shown to be a viable means of rapidly stabilizing landfills through aerobically-enhanced waste degradation. Aerobic stabilization has an additional benefit of reducing landfill emissions of methane, a potent greenhouse gas, which normally occur during anaerobic decomposition of landfilled waste. However the value of reduced methane emissions from aerobic stabilization of landfills has not been realized due to the difficulty of verifying methane destruction during aerobic treatment. The authors propose a framework for monitoring methane destruction in an aerobic stabilization system for use in verifying greenhouse gas emission reductions based on comparing the initial composition of the landfill gas with the composition of the exhaust gas from an aerobic stabilization system.

1. INTRODUCTION

The aerobic stabilization of landfilled waste by artificial injection of air into a landfill has been a subject for research for many years, with several case studies indicating enhanced waste degradation, processing of leachate, elimination of odors, and reduced methane emissions. Anaerobic conditions that characteristically develop in conventional landfills result in methanogenic decomposition, whereby organic carbon materials are metabolized into methane and carbon dioxide. In contrast, aerobic stabilization fundamentally changes the degradation process by utilizing aerobic bacteria, which consume oxygen and nutrients in the waste to metabolize organic carbon materials into carbon dioxide, water, and biomass.

Methane emissions from landfill facilities are recognized as a significant source of greenhouse gas emissions. Methane is a fairly potent greenhouse gas, with a global warming potential 21 times that of carbon dioxide (IPCC, 1995). In 2005, methane from solid waste activities in the United States alone generated 165.4 Terragrams of carbon dioxide equivalent (Tg CO2e), accounting for 2 percent of the total U.S. greenhouse gas emissions (EPA, 2001).

Internationally, landfill methane collection and destruction has developed as one of the primary methods for developing certified emission reduction units under the Kyoto Protocol's Clean Development Mechanism (CDM), with 21.21 percent of all registered CDM projects being waste or waste handling methods (UNFCCC, 2007). The general accessibility and ease in verifying methane destruction at landfills makes these attractive projects under the CDM.

However even with the amount of interest in capture and destruction of landfill methane for CDM emission reduction credits, there has not been developed an established protocol for crediting the methane destruction that occurs during the aerobic stabilization of a landfill. Given that the aerobic stabilization process both destroys existing methane in landfill gas and rapidly reduces the potential for waste to generate methane, the aerobic stabilization technology has considerable value in reducing greenhouse gas emissions. This paper presents a possible protocol for consideration in certifying aerobic stabilization projects under the CDM.

2. THE AEROBIC LANDFILL PROCESS

The waste material in the conventional landfill typically degrades by anaerobic degradation. This is an extremely slow process that produces objectional gases and other by-products potentially harmful to the environment. Under typical anaerobic conditions established in conventional landfills, the biodegradable waste material is entombed in a virtually dry and oxygen-deficient state. Because the landfill lacks necessary oxygen and moisture, there is very limited biodegradation and the degradation which does occur is characteristically anaerobic. The degradation is very slow and it can take from twenty to thirty years or more for the process to stabilize to a point where there is no further need for monitoring. During the long degradation period, emissions from the degrading organic material contain objectionable odors and methane gas (Ritzkowski, Heyer, et al., 2006).

Many of the negative features of conventional landfill operation are mitigated through aerobic stabilization. In an aerobically stabilized landfill, an engineered system is used to inject air into the waste mass to establish conditions within the landfill that promote and maintain aerobic degradation of the waste material. The air is injected in sufficient quantities to both supply aerobic bacteria with oxygen and to provide cooling by removing heat generated from the aerobic decomposition process. Moisture is added to the landfill to accommodate aerobic bacteria and to increase the ability of the air flow to remove heat from the aerobic landfill. Either water or leachate can be used in applying moisture, which has the additional advantage of being a means of processing leachate (Read, Hudgins et al., 2001).

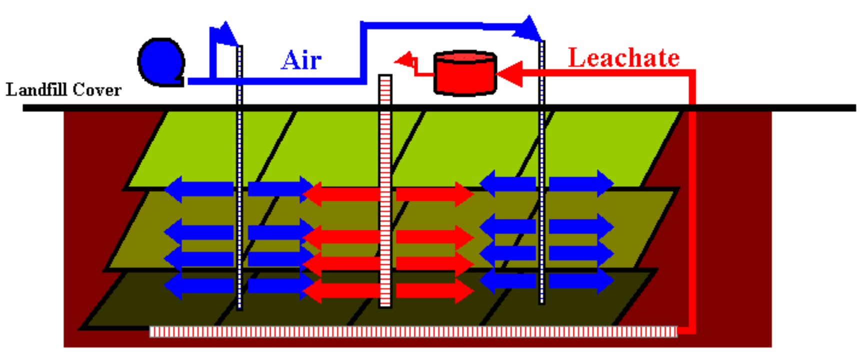

Figure 1: The Aerobic Stabilization Process at a Landfill

An aerobic stabilization system typically includes a grid of air injection wells and moisture or water injection wells throughout the landfill, such as is shown in Figure 1. The amount of water and oxygen (in the form of compressed air) injected into the landfill mass is regulated in response to a monitoring system that monitors temperature, oxygen content, and moisture content. The monitoring system may also monitor the generation or production of gases within the landfill as an indication of the type of degradation occurring. For example, the presence and concentration of methane gas generated in the landfill mass is a strong indication of anaerobic conditions in the landfill. Methane is a primary by-product of anaerobic degradation. If methane is maintained generally less than 10% by volume and no strong odors are detected from the by-products, this is a strong indication that aerobic degradation is being maintained, particularly if air or oxygen is being injected into the system and oxygen concentrations are maintained greater than 0% by volume. Methane concentrations approaching 50% is a strong indication that the waste degradation is primarily anaerobic (Read, Hudgins et al., 2001).

Oxygen is injected into the landfill to promote and maintain aerobic degradation of the waste material. Preferably, compressed air is the source of oxygen and is injected into the landfill mass through injection wells to ensure that the oxygen content remains above 0 percent. In this manner it is ensured that sufficient oxygen is being supplied to sustain aerobic degradation. So long as oxygen is being supplied into the landfill and the oxygen concentration in the landfill remains relatively low, generally just above 0 percent, it is ensured that sufficient oxygen is being supplied to promote and maintain primarily aerobic degradation.

Temperature within the landfill mass can be controlled by a combination of factors, but is controlled primarily through the injection of air and moisture into the landfill. The additional flow and heat capacity of the moisture provide an effective means of removing heat from the system. The temperature is also dependent on the moisture content. However if temperature in the landfill is being driven higher than 60 ºC, additional air and moisture can be injected into the system to remove heat and drive the temperature back into the ideal range (Lee, Lee, et. al, 2002).

Temperature is also monitored as an indication of complete or stabilized degradation. A decrease in temperature in the landfill despite an increase in oxygen levels is a strong indication that the degradation process is nearly complete and that the biodegradable material has stabilized. At this point, the waste material has been essentially composted and the landfill is stabilized. Additional monitoring of the landfill may no longer be needed (Das, Smith, et al., 2002).

3. CDM REQUIREMENTS FOR CERTIFYING EMISSION REDUCTIONS

To obtain credit for emissions reductions under the CDM, applicants for credit must demonstrate that the project activity is anticipated to result in a reduction in greenhouse gas emissions that are additional to any that would occur in the absence of the proposed project. Also the project must use baseline and monitoring methodologies that either have been previously approved by the CDM Executive Board or that follow approved procedures for establishing a new methodology (CMP, 2005). If a new baseline or monitoring methodology is proposed, the proposed methodology is submitted to the CDM Executive Board for review prior to registering the project activity in the CDM.

To qualify for CDM monitoring requirements, a monitoring plan must be prepared and submitted for approval that accounts for the following:

- Collection of relevant data for estimating emissions of greenhouse gases occurring within the project boundary,
- Collection of relevant data necessary for determining baseline emissions,

- Quality assurance and control procedures for monitoring,
- Procedures for the periodic calculation of the reductions of anthropogenic emissions by sources resulting from a CDM activity,
- Documentation activities.

The monitoring plan must be based on a previously approved monitoring methodology or a new methodology that is determined to be appropriate to the circumstances of the proposed activity and has been successfully applied elsewhere, or reflects good monitoring practice appropriate to the type of project activity. An independent review of the project monitoring is also required to certify the reported reductions in greenhouse gas emissions. This includes an on-site inspection, a review of performance records, collection of measurements, observation of established practices, and the testing of monitoring equipment (CDM, 2005).

4. REVIEW OF EXISTING APPROVED METHODOLOGIES

For aerobic stabilization projects, existing methods for baseline and additionality are adequate for demonstrating baseline emissions and that all reductions due to an aerobic stabilization project are additional to emissions reductions that would otherwise occur.

Two standards that are relevant to establishing an aerobic stabilization project baseline are CDM Method ACM0001/Version 05, consolidated baseline methodology for landfill gas project activities, and AM0025/Version 02, Avoided emissions from organic waste through composting. The consolidated baseline methodology defines the baseline for landfill gas project activities as the atmospheric release of the gas, considering that some of the methane generated by the landfill may be captured and destroyed to comply with regulations or contractual requirements, or to address safety and odor concerns. The baseline emissions are calculated as:

$$BE_y = (MB_y - MD_{reg,y}) \times GWP_{CH4}$$

Where BE_y is the baseline emissions in year y, MB_y is the methane produced in the landfill in the absence of the project in year y, $MD_{reg,y}$ is the methane that would be destroyed in the absence of the project activity in year y, and GWP_{CH4} is the global warming potential for methane. Subsequent approved versions of this method define the quantity of methane projected to be generated during a given year by use of a first order decay equation;

$$CH4_{projected,y} = k \times L_o \times \sum_{t=0,y} WASTE_{contract,t} \times e^{-k(t-y)}$$

Where $CH4_{projected,y}$ is the quantity of methane projected to be generated in a given year y, k is the waste decay rate, L_o is the methane generation rate, and $WASTE_{contract,t}$ is the quantity of waste disposed of at the landfill during each year t. This estimate of $CH4_{projected,y}$ is an appropriate baseline estimate for a landfill facility planning an aerobic stabilization project in the same manner as it is appropriate for a project planning for a landfill gas project. This estimate can be further refined by the multiphase first order decay equation used in AM0025/Version 02 for composting projects if the fraction of different waste types is reasonably well known. Any methane that is captured and destroyed to comply with regulations, contractual requirements, or to address safety or odor concerns should be subtracted from $CH4_{projected,y}$ to determine the appropriate level of baseline emissions.

Both method ACM0001 and AM0025 require the use of the CDM Executive Board’s Tool for the demonstration and assessment of additionality, Version 03, to establish project additionality. This requires an identification of alternatives to the project, an investment analysis to determine if the project activity is unlikely to be the most financially attractive alternative absent a CDM project designation, a barrier analysis to evaluate the feasibility of the identified alternatives, and a common practice analysis to compare the project with standard practice at similar facilities. Both of these approaches for determining baseline and additionality are readily applicable to aerobic stabilization projects.

The difficulty with these methodologies is establishing a monitoring framework for an aerobic stabilization CDM project that is amenable to the CDM verification process. In Method ACM0001, the approved monitoring methodology is based on a direct measurement of the amount of landfill gas captured and destroyed at the flare. Continuous monitoring is provided for the quantity and quality of landfill gas that is flared, with a determination made of the quantity of methane captured, quantity of methane flared, and the quantity of methane used to generate electricity. Measurements of methane fraction, temperature, pressure, and flow rates at discreet points in the landfill gas handling system provide quantitative estimates of these values that are readily subject to verification. This protocol cannot be applied to an aerobic stabilization system as the method destruction occurs in the landfill and not a control flare where methane destruction can be monitored.

The approved methodology for avoided methane emissions from waste composting, AM0025/Version 02, provides some insights for monitoring an aerobic stabilization project, but presents some difficulties as well. The total emissions reduction for an organic waste composting project is computed as follows:

$$ER_y = BE_y - PE_y - L_y$$

Where ER_y is the emissions reduction in year y, BE_y is the emissions in the baseline scenario in year y, PE_y is the emissions in the project scenario in year y, and L_y is the project leakage in year y. The baseline emissions are the estimates made from a multiphase first order decay equation, as described above. The project emissions are calculated as the sum of emissions from off-site electricity consumption, on-site fuel consumption, production of nitrous oxides during composting, and methane production from the anaerobic fraction of the composting solid waste. The percentage of waste in anaerobic conditions is determined from a sampling program within the compost pile. The leakage is calculated as carbon dioxide emissions from off-site transportation of waste materials to the composting facility.

The waste composting methodology can be directly applied to an aerobic stabilization of landfilled waste project given that sufficient waste characteristics are known that a multiphase first order decay model can be applied in determining BE_y. Whereas a waste composting facility can monitor waste characteristics as the waste is delivered to the facility, landfills typically do not have sufficient records to characterize the proportions of waste types anticipated in Method AM0025/Version 02. Therefore the authors believe a more direct approach to monitoring greenhouse gas emissions reductions is needed when evaluating emission reductions from aerobic stabilization projects.

5. PROPOSED METHODOLOGY FOR VERIFICATION

To provide a means of measuring greenhouse gas emissions reductions, the authors propose a monitoring program that characterizes the quality of landfill gas prior to operating an aerobic stabilization system with the quality of gas exhausting from an aerobic stabilization system to determine a reduction in methane emissions resulting from the project activity. The difference between the two concentrations multiplied by the volumetric flow rate of the exhaust gas that is not flow-through air from the system injection, less the emissions resulting from external offsets such as electrical power consumption, less the amount of nitrous oxides generated in the aerobic system would establish the amount of emission reductions as a result of the project activity. The emissions reduction from an aerobic stabilization project can be expressed as follows:

$$ER_y = (C_{LFG-CH4} - C_{EXH-CH4,y}) \times (1 - \frac{C_{EXH-O2,y}}{C_{INJO2,y}}) \times GWP_{CH4} - PE_{elect,y} - PE_{N2O,y}$$

Where $C_{LFG-CH4}$ is the concentration of methane in the anaerobic landfill gas prior to implementing aerobic stabilization, $C_{EXH-CH4,y}$ is the concentration of methane in the exhaust gas averaged over year y, $C_{EXH-O2,y}$ is the concentration of oxygen in the exhaust gas averaged over year y, C_{INJ-02} is the concentration of oxygen in the injection air, GWP_{CH4} is the global warming potential for methane, $PE_{elect,y}$ is the project emissions resulting from off-site power consumption in year y, and $PE_{N20,y}$ is the project emissions resulting from nitrous oxide formation in year y.

The proposed monitoring methodology assumes that oxygen consumed in the system is either reducing methane or used in metabolizing biomass that otherwise would generate methane anaerobically, and that oxygen remaining in the exhaust gas is from air injected into the aerobic system that has not been consumed from aerobic processes, and therefore represents flow-through air in the system. If no oxygen is present in the exhaust gas, then the entire exhaust stream can be considered process gas from the aerobic stabilization system and the amount of methane reduction in the volumetric flow rate measured represents a true reduction in methane from the aerobic system. The consumption of oxygen from other reduced compounds such as ammonia and sulfides is accounted for in the initial concentration of methane in the anaerobic landfill gas, which does not include these reduced compounds.

The offsets from electrical power consumption or diesel power generation to operate the aerobic stabilization system must be accounted for as a component of project additionality. These emission sources can be determined using standard CDM methods approved for estimating such emissions (UNFCC, undated).

The operation of an aerobic stabilization system has the potential to create conditions conducive to nitrous oxide formation, which should be accounted for in the determination of additionality. Nitrous oxide concentration should be monitored in the exhaust gas and multiplied by the total flow rate and the global warming potential for nitrous oxides to determine the offset resulting from these compounds.

The aerobic stabilization system must be appropriately engineered to accommodate greenhouse gas emissions reduction monitoring. This would include a network of passive vent wells or active extraction wells from which exhaust gas flow could readily be monitored and tested using standard continuous emissions monitoring equipment. Ideally the exhaust system should be connected to a manifold to reduce the number of monitoring points and therefore the potential for observational or equipment error in the monitoring process. Appropriate instrumentation should be installed in both the air injection system and the gas exhaust system to provide suitable monitoring data for verification purposes.

6. PROPOSED STUDY

The authors propose an evaluation of aerobic stabilization systems using the procedures identified in this paper to asses the suitability of the proposed approach to monitoring greenhouse gas emission reductions at landfills utilizing an aerobic stabilization system. Two sites using aerobic stabilization systems will be designed and monitored consistent with this proposal; one in the Southeastern United States and one in Sicily, Italy. Both sites anticipate using aerobic stabilization technology for rapid waste stabilization, and will document greenhouse gas emissions reductions as research to evaluate the proposed monitoring methodology.

A site assessment of both landfills will occur prior to the design of the aerobic stabilization system. Included in the site assessment will be site surveys and an estimate of landfill volume, an exploratory drilling program to characterize the waste, sampling of landfill gas, and the construction of pressure monitoring probes to evaluate landfill gas generation rates and the pneumatic properties of the landfill. The purpose of the site assessment is to provide sufficient data to design an aerobic stabilization system for evaluating the proposed monitoring methodology.

Samples of waste from the exploratory drilling will be submitted to an analytical laboratory to characterize moisture content and biochemical methane potential (BMP) as a measure of degradable organic carbon in the waste. Landfill gas will be sampled for methane, carbon dioxide, oxygen, nitrogen, hydrogen sulfide, ammonia, and other volatile organic constituents.

Pressure monitoring probes and extraction wells will be constructed in each of the exploratory borings. Pressure probes will consist of 25 mm polyvinyl chloride (PVC) pipe with perforated ends, installed in isolated nests within each borehole. Extraction wells will consist of 100 mm perforated PVC pipe installed through a significant section of the landfill to facilitate horizontal flow during a pump test. Figure 2 illustrates the monitoring system used for measuring gas generation rate and the pneumatic properties of the landfill.

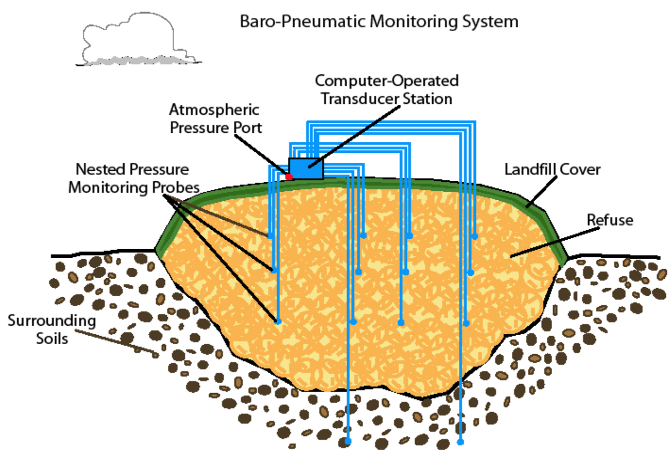

Figure 2: Landfill Monitoring System

Due to the inherent difficulties in estimating landfill gas generation from pump tests alone (e.g., Walters, 2003), a barometric pressure-response method will be used to estimate landfill gas generation. This approach consists of accurate measurement and analysis of the pressure response in the landfill to natural variations in barometric pressure. Pump tests are also performed to provide an estimate of horizontal permeability and air porosity in the landfill. The methodology is based on sound gas flow principles and independent estimates of the gas permeability of the cover, refuse, and surrounding soil.

This barometric pressure-response method assumes that pressure distribution within a landfill depends on the rate of landfill gas production; the effective gas permeability and air-filled porosity of landfill refuse, underlying soil, and overlying cover materials; and the barometric pressure at the landfill boundaries. Landfill gas pressures increase with landfill gas production rates and decreased gas permeability, while the transient barometric pressure response is attenuated with depth as a function of the pneumatic diffusivity. The gas permeability and landfill gas generation rate both can be estimated by appropriately analyzing the transient pressure responses at various depths within and beneath the landfill. Given a relatively constant rate of landfill gas generation during the test period, the only factors affecting gas pressures at fixed measuring points will be changes in boundary pressures related to changes in barometric pressure and the gas permeability. In the case of an unlined landfill, gas movement through the sides of the landfill below grade and through the base of the landfill must also be considered in estimating gas generation rates. This approach has been successfully applied to landfill gas generation rate estimates at several landfills in the United States (Bentley, Smith, et al., 2005).

The results of the site assessments will be used as the basis for the design of the aerobic stabilization system at each site. Air and moisture delivery requirements will be estimated based on waste characteristics. The pneumatic properties of the landfill will be used to design an efficient spacing of air injection wells along with the size of an air distribution piping system and regenerative blower capacity. Similarly the pneumatic properties of the landfill will be used to design an efficient gas exhaust system, either active or passive. A numerical model of the aerobic stabilization system will be constructed to provide an estimate of system efficiency and operating parameters.

Upon completion and approval of the aerobic stabilization system designs, the systems will be constructed and operated under a monitoring plan to determine the greenhouse gas reduction effectiveness. The monitoring plan, at a minimum, will include the operational parameters listed in Table 1.

The aerobic stabilization systems will be monitored for a period of one year using the protocol outlined in this paper. Upon completion of the first year of data, the data will be reviewed and summarized in a system monitoring report. The system monitoring report will evaluate the suitability of the proposed protocol, and make recommendations for any modifications that may be necessary. If appropriate, the system monitoring report will be in a format that can be used as the basis for a proposed new monitoring methodology in association with a CDM project registration application on subsequent projects.

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Table 1 - Aerobic Stabilization System Monitoring Parameters

Parameter	Description	Units	Location
Q_{Air}	Volumetric flow rate of air	M^3/min	Injection gas stream, exhaust gas stream
T	Temperature	ºC	Injection gas stream, exhaust gas stream, landfill interior
W	Moisture content	% (Vol)	Injection gas stream, exhaust gas stream
Q_{water}	Application rate of water or leachate	L/min	Water/leachate supply
P	Pressure	kPa	Landfill interior
E	Imported electricity	kWh	Power supply
CH_4	Methane content	% (Vol)	Injection gas stream, exhaust gas stream, landfill interior
CO_2	Carbon dioxide content	% (Vol)	Injection gas stream, exhaust gas stream, landfill interior
O_2	Oxygen content	% (Vol)	Injection gas stream, exhaust gas stream, landfill interior
N_2	Nitrogen content	% (Vol)	Injection gas stream, exhaust gas stream, landfill interior
H_2S	Hydrogen sulfide content	% (Vol)	Exhaust gas
NH_3	Ammonia content	% (Vol)	Exhaust gas