

## ABSTRACT

AZAM, HOSSAIN MOHAMMAD MUYEED-UL-. Oxidation of Methane in Landfill Covers. (Under the direction of Dr. Morton A. Barlaz.)

Yolo County, CA is planning to optimize landfill gas collection by storing gas in the landfill during off peak periods by reducing the vacuum on the gas collection system and collecting gas during times of peak power demand. The objective of this research was to evaluate the efficacy of this approach by evaluating whether gas emissions would increase at low vacuum. Biologically active covers composed of compost/wood chips (80/20), pure compost, or green waste at thicknesses of 0.31 to 0.9 m were tested using static chambers to measure methane emissions and oxidation potential during rainy and dry season. In addition, laboratory column tests were conducted with two year old green waste to evaluate the effects of pressure gradient, moisture addition to simulate the dry and rainy seasons in California, and continuous vs. intermittent methane feed.

The effect of climate was significant. In the field, the highest CH<sub>4</sub> emission was 20.85 gm CH<sub>4</sub>/m<sup>2</sup>-d in 0.91 m compost + wood chips and 5.255 gm CH<sub>4</sub>/m<sup>2</sup>-d in 0.31 m soil during the rainy and dry seasons, respectively. CH<sub>4</sub> oxidation varied from 5 to over 99% when it was measured using stable isotope technique. In the rainy season tests, there was a statistically significant decrease in CH<sub>4</sub> emissions when the gas system vacuum was increased for the covers with the highest emissions (0.91 m compost + wood chips, 0.31 m compost, soil). In contrast, there was not an increase in CH<sub>4</sub> emissions associated with reduced gas collection system vacuum during the dry season tests. The average flux rate in dry season was below 5.255 gm CH<sub>4</sub>/m<sup>2</sup>-d in all the covers both for low and high vacuum. While there were many confounding issues, emissions at low vacuum during the rainy season were the highest. Overall, all covers tested were effective in controlling gas release. The emissions data are consistent with the soil gas profile data where CH<sub>4</sub> concentrations for the dry season were in the ppmv range while the corresponding concentrations were in the % range for the rainy season tests.

Laboratory columns were filled with 2 year old green waste that is used at the Yolo County landfill as a daily cover. In most cases, methane oxidation decreased as the flux or pressure gradient increased. The addition of moisture inhibited methane oxidation by

restricting O<sub>2</sub> diffusion in the green waste as evidenced by the reduced O<sub>2</sub> concentrations at depth in the water addition columns. The inhibitory effect of water addition on methane oxidation was most apparent at the end of the experiment at the CH<sub>4</sub> feed rate of 147.2 gm/m<sup>2</sup>-day. Moreover, the average CH<sub>4</sub> uptake data do not suggest any effect associated with pulsed flow in CH<sub>4</sub> oxidation. The maximum oxidation rate measured in this study was 664.2 gm CH<sub>4</sub>/m<sup>2</sup>-d but was only measured in one of the eight columns.

Both the field and laboratory results indicate that high moisture can inhibit methane oxidation. It is encouraging to note that during the dry season, there was no increase in emissions during periods when the gas collection system vacuum was reduced. There was an increase in CH<sub>4</sub> emissions at low vacuum during the rainy season. However, this may not be critical as the hottest temperatures and associated highest demand for electricity are likely to occur during the dry season. Except for the soil and 0.31 m green waste, all covers of different thicknesses performed well. Therefore, the cover type to be used in the field should be based on availability of the material and cost.

**OXIDATION OF METHANE IN LANDFILL COVERS**

by  
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## **DEDICATION**

Dedicated to my family members Md. Mofazzal Hossain, my father; Ms. Azmatun Naher, my mother; Hossain M Anam and Hossain M Asif, my brothers.

## **BIOGRAPHY**

Hossain Azam was born in Dhaka, Bangladesh and grew up in different places of Bangladesh. He is the eldest son of Md. Mofazzal Hossain and Ms. Azmatun Naher. He completed his undergraduate degree in civil engineering from Bangladesh University of Engineering and Technology (BUET). After completing his degree, he worked as a faculty member in Military Institute of Science and Technology (MIST) and in University of Asia Pacific (UAP), Bangladesh for more than 2.5 years. Now he is studying his MS degree in Environmental Engineering at North Carolina State University (NCSU). His graduate research is on methane oxidation of landfill biocover. His research interests include solid waste management, groundwater remediation, drinking water and wastewater treatment. His future plan is to pursue PhD and make meaningful contribution to the society through environmental engineering practice.

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## Introduction

Global warming is the direct consequence of the increase in the atmospheric concentration of 'greenhouse gases' including CH<sub>4</sub>, CO<sub>2</sub>, trace gases, water vapor, ozone, nitrous oxide, and chlorofluorocarbons (US EPA, 2006). CH<sub>4</sub> is the most abundant hydrocarbon present in the atmosphere with an average concentration of 1.7 ppm (Le Mer and Roger 2001; Borjesson and Svensson, 1997a). It has 21 times the global warming potential of CO<sub>2</sub> by mass over a 100-year time period (US EPA, 1990) and atmospheric CH<sub>4</sub> has increased by a factor of 2 over the last century.

CH<sub>4</sub> is emitted to the atmosphere both from natural and anthropogenic sources. Natural sources include wetlands, tundra, bogs, swamps, termites and wildfires. Major anthropogenic sources include landfills, natural gas and oil production and processing, coal mining and agriculture. Worldwide, CH<sub>4</sub> emissions from landfills are estimated to account for over 730 million metric tons of carbon dioxide equivalent (MtCO<sub>2</sub>eq) in 2000 which was over 12% of total global CH<sub>4</sub> emissions (US EPA, 2006). Landfill CH<sub>4</sub> also accounts for 37% of anthropogenic U.S. CH<sub>4</sub> emissions and a reduction in CH<sub>4</sub> emissions is a key objective of the U.S. Climate Change Action Plan (US EPA, 1999).

CH<sub>4</sub> and CO<sub>2</sub>, which comprise over 99% of landfill gas (LFG), are produced during the anaerobic decomposition of refuse in landfills. Unlike other greenhouse gases, CH<sub>4</sub> can be used to produce energy as it is the main component (95%) of natural gas. Despite its potential as a fuel resource, effective storage and collection of CH<sub>4</sub> can be a major challenge.

The major control on CH<sub>4</sub> emissions from landfills is to collect LFG and burn it in a flare or utilize it for energy recovery. Gas recovery systems can be an effective strategy to mitigate CH<sub>4</sub> emissions from landfills. Field studies have shown that CH<sub>4</sub> emissions decreased more than three orders of magnitude adjacent to recovery systems (Bogner et al., 1993). Reductions of 75-90% of the emitted CH<sub>4</sub> through the use of LFG recovery systems have been reported (Mosher et al., 1996).

CH<sub>4</sub> may also be oxidized in landfill covers by methanotrophic bacteria (Whalen et al., 1990; Kightley et al., 1995; Czepiel et al., 1995; Chanton and Liptay, 2000; Borjesson et al., 2001). Reported values of CH<sub>4</sub> oxidation vary widely based on cover types, climatic conditions and presumably based on the LFG flow rate. Field studies show that CH<sub>4</sub> emissions fluctuate daily and seasonally and are affected by climate (Jones and Nedwell,

1993; Borjesson and Svensson, 1997b; Kjeldsen et al., 1997). Landfill covers had been reported to oxidize CH<sub>4</sub> from about 7% to 50% of the total amount (Reeburgh, 1996; Kightley et al., 1995; Gardner and Manley, 1993). Czepiel et al. (1996a) calculated 10% CH<sub>4</sub> oxidation in a landfill in the northeastern U.S. over a 12 month period in which temperature fluctuations were considered. Recently Barlaz et al. (2004) reported a mean CH<sub>4</sub> oxidation of 55% and 21% in a biologically active cover constructed of compost and soil, respectively. Moreover nearly 100% oxidation had been reported in the literature (Kjeldsen et al., 1997). Even consumption of atmospheric CH<sub>4</sub> is possible under certain conditions (Bogner et al, 1995; Borjesson et al 1998a; Barlaz et al., 2004).

When CH<sub>4</sub> is converted to electrical energy, it has an economic value in addition to its value as a CO<sub>2</sub>-neutral source of renewable energy. To the extent that the electricity can be sold during periods of peak demand, the CH<sub>4</sub> is most valuable. The Department of Public Works in Yolo County, California is exploring different ways to optimize the utilization of CH<sub>4</sub> generated during waste decomposition. One possibility is to capture CH<sub>4</sub> during times of peak power demand and to store the LFG in the landfill during the off peak periods. Gas recovery would be controlled by adjusting the vacuum on the LFG collection system. To evaluate this peak power recovery concept, it is important to demonstrate that emissions to the atmosphere do not increase when the LFG collection system vacuum is reduced as the pressure gradient between the landfill and atmosphere is increased.

One method for mitigating increased CH<sub>4</sub> emissions is the utilization of covers that are designed to enhance methane oxidation. The objective of this research was to evaluate the efficacy of the peak power LFG recovery concept. Laboratory-scale columns were utilized to evaluate the performance of a biologically active cover material and to assess the effects of (1) pressure gradient, (2) moisture infiltration and (3) continuous vs. pulsed methane flow. Field-scale experiments were conducted to assess the performance of several different cover materials under varying climatic conditions and LFG collection vacuum.

## **Literature Review**

### **CH<sub>4</sub> Emission: Global and US**

Since the 1700s, rapidly growing human activities like agriculture, fossil fuel use and waste disposal have increased CH<sub>4</sub> emissions by more than 2 orders of magnitude. Annual CH<sub>4</sub> emissions were estimated at around 300 Tg in 2000 and are projected at 400 to 600 Tg in 2010 by International Panel of Climate Changes (IPCC) (Le Mer and Roger, 2001). Landfills are major contributors of atmospheric CH<sub>4</sub>, emitting from 19 to 40 Tg yr<sup>-1</sup> worldwide (Doorn and Barlaz, 1995). More recently, a study based on per capita waste generation estimated CH<sub>4</sub> emissions ranging from 16 to 57 Tg CH<sub>4</sub> yr<sup>-1</sup> (Bogner and Matthews, 2003).

The United States is the largest emitter of greenhouse gases and accounts for more than 20% of global emissions (UN Publications, 2004). In 2002, the US emitted about 659 million tons CH<sub>4</sub> of total 7644 million tons of greenhouse gases expressed as CO<sub>2</sub> equivalents. Landfills are responsible for approximately 32% of these CH<sub>4</sub> emissions which is 3% of the total greenhouse gas emissions of the country (USEPA, 2006). The present atmospheric CH<sub>4</sub> concentration of 1.8 ppmv is the highest on record (Humer and Lechner, 2001).

### **Present Status of Landfill**

Landfills are a significant waste repository; approximately 55% by weight MSW generated in US was disposed off in the landfills in 2001 despite the increase in recycling and composting (US EPA, 2001). The Environmental Protection Agency (EPA) established the Landfill Methane Outreach Program in 1994 to promote the development of landfill gas to energy projects in the US. It is estimated that there are currently 2300 active landfills in the United States. There are already 382 landfills with gas recovery systems in place and there are many more potential landfills to use the gas. As of 2005, EPA identified 630 candidate landfills for energy projects (Jaramillo and Matthews, 2005). Currently there are 1100 commercial landfill gas recovery projects worldwide (Willumsen, 2003).

The Kyoto Protocol has provided a new stimulus for commercial landfill gas recovery projects in developing countries under the Clean Development Mechanism (CDM). Through CDM, developed countries can invest in projects like landfill gas collection projects in the

developing countries through the purchase of Certified Emission Reductions (CERs). The CERs can be effectively used by the developed countries to meet their Kyoto greenhouse gas reduction targets (Lee et al., 2005). Landfill gas recovery projects were the second largest suppliers of emission reductions worldwide as of May, 2004 (Lee et al, 2005).

### **Regulation**

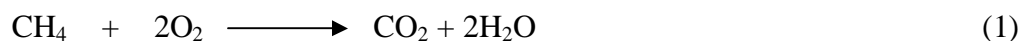
New Source Performance Standard (NSPS) require large landfills (at least 2.5 million megagrams (Mg) and 2.5 million cubic meters in size) with estimated non-methane organic compound (NMOC) emissions of at least 50 Mg/yr to collect and control or treat LFG. LFG can be controlled by combusting it in a boiler, engine or turbine to produce steam or electricity, taking advantage of LFG as renewable energy source (USEPA, 2006).

The U. K. and the European Union have adopted the strategy of increased gas collection and systematic reductions in the quantity of biodegradable waste that is buried (Hilger and Humer, 2003). Countries like Germany and Austria have set quantitative limits on the allowable total organic carbon (TOC) of landfilled waste to reduce CH<sub>4</sub> generation (Hilger and Humer, 2003).

### **Methane oxidation**

Landfill cover is located at the interface of anaerobic and aerobic systems. In this region, the cover is exposed to high CH<sub>4</sub> from below and O<sub>2</sub> concentrations from above that diminish with depth. CH<sub>4</sub> follows the path of least resistance to migrate through the cover system and sometimes a decrease in cover permeability causes the gas migrate laterally. This is a particular problem in old landfills with no gas venting or collection systems (Visvanathan, 1999). Some fugitive emissions of CH<sub>4</sub> are also observed in landfills with passive or active collection system (Hilger and Barlaz, 2006).

An alternative tool for managing gas emissions is to incorporate a biocover into the design of a landfill cover. Biocovers made of compost can ensure optimal ambient conditions for methanotrophic bacteria, foster microbial activity and attain very high oxidation rates (Humer and Lechner, 2003). Landfill CH<sub>4</sub> is converted to water, CO<sub>2</sub> and biomass by methanotrophic bacteria in the landfill cover.



Methanotrophs contain the CH<sub>4</sub> mono-oxygenase enzyme that enables them to utilize CH<sub>4</sub> as a source of energy and as a carbon source. It is a subset of a highly diverse group of bacteria called methylotrophs that can metabolize C-1 compounds (Hanson and Hanson, 1996). Other bacteria notably ammonia oxidizers and even some yeast can oxidize CH<sub>4</sub> (References cited in Hilger and Humer, 2003).

### **Available Techniques for Measurement of Methane Emission and Oxidation**

CH<sub>4</sub> emissions can be measured using static chambers and inert atmospheric tracer methods. The reported results are within <10% difference among these flux techniques (Mosher et al., 1999) despite their inherent advantages and disadvantages (Czeipal et al., 1996b). New micrometeorological techniques to measure CH<sub>4</sub> emissions in landfill using tunable diode laser (TDL) have been also reported (McBain et al., 2005).

In the static chamber method, a stainless steel collar and a lid are placed over a landfill surface to measure CH<sub>4</sub> concentration over time. At a beginning of a test, the lid is placed over the collar with a valve kept open to preclude a pressure increase. CH<sub>4</sub> measurement should be sufficiently short so that a pressure build-up does not occur inside the static chamber. The following equation is used to calculate the flux:

$$\text{Flux} = V/A \cdot \Delta c / \Delta t \quad (2)$$

Where, V is the static chamber volume, A is the surface area enclosed by the chamber,  $\Delta c / \Delta t$  is the slope of a plot of CH<sub>4</sub> concentration vs. time. Flux data then can be converted to a mass emission rate by using the ideal gas law. More detail is presented in the literature (Barlaz et al., 2004, Czepiel et al., 1996b)

In the atmospheric tracer test, pure sulfur hexafluoride (SF<sub>6</sub>) or N<sub>2</sub>O is normally released from the emitting surface. If the released tracer is well mixed in the source plume, then the CH<sub>4</sub> emission can be calculated from the following equation:

$$Q_M = Q_T \frac{C_M \cdot M_M}{C_T \cdot M_T} \quad (3)$$

Where, Q<sub>M</sub> is the CH<sub>4</sub> flux rate, Q<sub>T</sub> is the tracer release rate, C<sub>M</sub> and C<sub>T</sub> are the measured concentration of CH<sub>4</sub> and tracer and M<sub>M</sub> and M<sub>T</sub> are the molecular weights of CH<sub>4</sub> and tracer. This method is sensitive to situations with no interfering sources, a sufficient signal to be measured against the background and a strong enough source to be measured far enough

downwind to ensure adequate mixing with the tracer gas under stable atmospheric conditions (Czepiel et al., 1996b). This method is well described in the literature (Galle et al., 2000).

CH<sub>4</sub> flux measurements were also obtained using micrometeorological mass balance measurement technique [integrated horizontal flux (IHF)] with two tunable diode laser trace gas analyzer (TDLTGA) systems. This method can be used for continuous, non-intrusive measurements of gas flux at high temporal resolution. Fluxes were measured using a mass balance approach known as integrated horizontal flux (IHF) technique (Wilson et al., 1983; Denmead et al., 1998). The mean flux (F) of a scalar gas is expressed as:

$$F = \frac{1}{L} \sum_{i=1}^N \overline{\Delta c_i} \overline{\Delta u_i} \overline{\Delta z_i} \quad (4)$$

Where, L is the horizontal distance of the emitting surface from the sampling location,  $\overline{u_i}$  is the mean horizontal wind speed at height i,  $\overline{\Delta z_i}$  is the depth of the layer of air between sample heights (i),  $\overline{\Delta c_i}$  is the difference in mean concentration of a gas before and after the volume of air has passed over the emitting surface and is measured at the sample height. Detailed procedures and techniques are described in the literature (McBain et al., 2005). The concentrations of CH<sub>4</sub> in the air samples were measured by two TDLTGA systems for which a detailed description is also available (Edwards et al., 2003)

The in-situ technique of determining CH<sub>4</sub> oxidation is based upon stable isotopes. CH<sub>4</sub> utilizing bacteria use <sup>12</sup>CH<sub>4</sub> preferentially to <sup>13</sup>CH<sub>4</sub> as substrate (Barlaz et al., 2004). Difference in δ<sup>13</sup>C between produced or anoxic zone CH<sub>4</sub> (which is not affected by oxidation) and the gas emitted from a cover (which has been subjected to oxidation) can confirm % CH<sub>4</sub> oxidation. Using this technique, % CH<sub>4</sub> oxidation calculation is only possible for positive emission. The details procedure is described in the literature (Barlaz et al., 2004, Chanton et al., 1999).

### **Relationship between Methane Emission and Oxidation**

Emission measurements can be used to qualitatively measure the performance of different levels and configuration of gas recovery and control (Mosher et al., 1999). CH<sub>4</sub> fluxes from landfills are not spatially uniform and there are often some hot spots where gas bubbles can often be observed in wet conditions (Abichou et al, 2006b).

Emissions measured on a landfill surface are highly variable and reported variation is seven orders of magnitude from less than 0.0004 to 4,000 gm/m<sup>2</sup>-day (Bogner et al., 1997). Landfill sections with geo-membrane cover showed emission rate ranging from 36 to 1750 gm/m<sup>2</sup>-day (Mosher et al., 1999). In case of uncovered section, the emission was in the range of 190-28500 gm/m<sup>2</sup>-day (Mosher et al., 1999). Flux values from the detection limit to 1495 gm/m<sup>2</sup>-day were reported in a MSW landfill covered with 1 to 2 m sandy-clay loam surface material with limited surface fissuring (Czepiel et al., 1996a). CH<sub>4</sub> flux varied from -13.6 to 1755 gm/m<sup>2</sup>-day at the entire facility in Leon County landfill, Florida that is covered with 15 to 100 cm sandy clay (Abichou et al., 2006b). However, field measurements of CH<sub>4</sub> emissions are quite limited in number (Borjesson et al., 2001). A narrower range of 9-130 gm/m<sup>2</sup>-day is reported at landfill sites of northeastern United States (Chanton et al., 1999).

CH<sub>4</sub> emissions from the biocover varied from -1.73 to 1.33 gm/m<sup>2</sup>-day based on four field measurements over 14 months period at the Outer Loop Landfill in Louisville, KY. The emissions pattern did not change due to the inactivation of the gas collection system in the biocover. Fluxes greater than 15 gm/m<sup>2</sup>-day (26% of tests) were measured as well as some dramatic effects due to deactivation of the gas collection system was also observed in soil cover (Barlaz et al., 2004). Total landfill emissions ranged from 150-250 gm/m<sup>2</sup>-day when a passive vent system was installed at a landfill site (Tohjima and Wakita, 1993). Total emission measurement was reported as 16 gm/m<sup>2</sup>-day after the test conducted after 16 years of the landfill closure in Russia (Nozhevnikova et al., 1993).

Oxidation values of 80% based on soil δ<sup>13</sup>C-CH<sub>4</sub> and radon profiles (Bergamaschi et al., 1998), 10% based on soil incubations and modeling (Czepiel et al., 1996) and warm season values 20-32% with annual average of 10% had been reported (Liptay et al., 1998). The highest CH<sub>4</sub> oxidation rates of 214.4 gm/m<sup>2</sup>-day was reported at a landfill in Austria using sewage sludge compost and wood chips as a cover material (Humer and Lechner, 2001). The CH<sub>4</sub> oxidation rates of 166 gm/m<sup>2</sup>-day (Kightley et al., 1995) and 100g CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup> (Visvanathan et al., 1999) are also reported in the field scale research. In a 2 day landfill CH<sub>4</sub> oxidation experiment, the oxidation rates increased and then decreased more than 2 orders of magnitude due to change in CH<sub>4</sub> concentrations when the pumped gas recovery system was shut down and restarted (Bogner, 1997).

The highest oxidation rate in a laboratory system reported previously, 410.1 gm CH<sub>4</sub>/m<sup>2</sup>-d, represents 100% oxidation in columns filled with municipal solid waste compost (Humer and Lechner, 1999). Other laboratory-scale CH<sub>4</sub> oxidation rates include 166 gm CH<sub>4</sub>/m<sup>2</sup>-day (Kightley et al., 1995), 100 gm CH<sub>4</sub>/m<sup>2</sup>-day (Visvanathan et al., 1999), and 144 gm CH<sub>4</sub>/m<sup>2</sup>-day (Stein and Hettiaratchi, 2000).

Summary of several emission and oxidation studies have been documented in Table 1 to 3. Different studies on methane oxidation in the laboratory cannot be compared due to variability in cover types, differences in diameter and height of columns, methane fluxes as well as different air flow rates. In the same way, comparison among the different field scale studies was difficult due to different types and thicknesses of covers, status of gas collection system, seasons of a year, age of the landfill and different sections of the landfills. But it is evident from the studies that the biocover performed better than soil cover to oxidize CH<sub>4</sub> and reduce CH<sub>4</sub> emission both in the laboratory studies (Berger et al., 2005; Humer and Lechner, 1999a; Humer and Lechner, 1999b; Stein and Hettiaratchi, 2001; Hilger et al., 2000; Visvanathan et al., 1999) and in field studies (Abichou et al., 2006a; Abichou et al., 2006b; Spokas et al., 2005; Barlaz et al., 2004; Humer and Lechner, 2001; Schuetz et al., 2003; Borjesson et al., 2001, Borjesson et al., 1997a, Chanton et al., 1999). Effectiveness of biocover are evaluated as long as 2 years till now (Humer and Lechner, 2001). It is observed that the long term durability and performance of biocover are yet to be documented in the literature.

Table 1: Flux and Oxidation Capacity in Laboratory Scale Research

Cover Type	Column Dimension	Flux (gm CH <sub>4</sub> /m <sup>2</sup> -d)	Oxidation <sup>a</sup> (gm CH <sub>4</sub> /m <sup>2</sup> -d)	Additional Info	Reference
Municipal Solid Waste Compost	60 cm long with 11 or 20 cm dia	410.1	168.9, 410.1, 345.8	60 weeks old, 45.7% Initial water content	Humer and Lechner, 1999 (Column Experiment, Austria)
		410.1	124.64, 289.5, 204.1	20 weeks old, 44.7% Initial water content	
		205.1	124.64, 205.1, 176.9	36 weeks old, 32.4% Initial water content	
Sewage sludge compost		151.2	40.7, 151.2, 130.3	34 weeks old, 48.5% Initial water content	
		88.45	3.2, 64.3, 32.2,	34 weeks old, 46.1% Initial water content	
		189	128.7, 188.2, 152.8	47 weeks old, 47.6% Initial water content	
Top soil		136.7	36.2, 62.72, 48.2	17.8% Initial water content	
Humic Garden Soil		201	108.6, 201, 144.7	17.1% Initial water content	
Loamy cover soil		265.35	96.5	Not Specified	
Sewage sludge compost	10 cm gravel overlaid by 90 cm sewage sludge compost	48.25	48.25	Initial water content 46%, Air flow rate 83.3 ml/min	Humer and Lechner, 1999 (Lysimeter Experiment, Austria)
30 cm mix of compost and silty sand over 90 cm silty sand	194 cm long with 19 cm inner dia	49.6 to 104	94% to 98% of feeding rate	Initial Water Content 16.6% of mix and 12.4 % of sand	Berger et al, 2005 (Column Experiment, Germany)
Mixture compost and silty sand with different compositions in 5 levels					

a. Where there are three entries in a cell denotes minimum, maximum and mean oxidation rate, otherwise is the value is the observed oxidation rate.

Table 2: Flux and Oxidation Capacity of Laboratory Scale Research

Cover Type	Column Dimension	Flux (gm CH <sub>4</sub> /m <sup>2</sup> -d)	Air Flow rate (mL/min)	Oxidation (gm CH <sub>4</sub> /m <sup>2</sup> -d)	% Oxidation <sup>a</sup>	Additional Info	Reference
Soil (70% sand, 15% or 5% silt, 15% or 25% clay)	120 cm long with 20 cm dia	91.5 to 164.7	300	50 to 63 (Maximum 100 at flux of 109.8)			Visvanathan et al., 1999 (Laboratory Column, Thailand)
Fresh soil (63 ± 8% sand, 31±5% silt, 7 ± 3% clay)	30.5 column soil with 15 cm dia	280.8	50		38± 1.4, 21± 0.45	Column Sparged with LFG only	Hilger et al., 2000 (Laboratory Colum, USA)
					35± 0.35, 17± 0.59	KCl Amended	
					40± 3.0, 20± 0.61	NO <sub>3</sub> Amended	
					32± 1.9, 14± 0.26	NH <sub>4</sub> Amended	
					45± 0.75, 20± 0.52	Lime Addition	
					39± 1.2, 16± 0.72	No Lime Addition	
					37± 4.6, 19± 1.0	Bare Soil	
					47± 1.0, 81± 1.7	Grass	
				28± 3.9, 19± 1.3	Grass + NH <sub>4</sub> + CH <sub>4</sub>		
Sedge Peat Mass (PM)	1 m long with 15 cm dia	319	300	Peak rate: 159.5		Moisture Content 316%, Organic Matter 79%, Porosity 0.9	Stein and Hettiaratchi, 2000 (Column Expeirment, Canada)
		160		Peak rate: 144			
Springbank Landfill Loam (LF)		319		102 to 120	50% Maximum		
Rockyview Dark Soil (RV)		186		93	100 Maximum	Moisture Content 9.4%, Organic Matter 3.1%, Porosity 0.6 to 0.61	
		310		10 at 6.1% moisture 124 at 10.2% moisture		Moisture Content 6 to 10.2%, Organic Matter 4.7%, Porosity 0.53	

a. Values are the average of replicates ± SE.

Table 3: Flux and Oxidation Capacity of Field Scale Research

Age of Waste (yrs)	Cover Type	Cover Thickness	Flux <sup>a</sup> (gm CH <sub>4</sub> /m <sup>2</sup> -d)	Oxidation (gm CH <sub>4</sub> /m <sup>2</sup> -d)	% Oxidation <sup>c</sup>	Gas Collection System, Slope	Reference
7*	Sandy Clay	30-60 cm	-13.6, 1754.8, 167.0, 24.0	.....	0, 60.4, 19.5, 16.6	No Collection, Flat	Abichou et al., 2006b (Field Scale, USA)
14		45 cm	-2.3, 63.1, 8.6, 2.1	.....	0, 53.2, 26.6, 26.6	No Collection, Slope	
1		15-30 cm	0, 521.2, 87.0, 32.7	.....	1.7, 36.3, 14.4, 14.7	No Collection, Flat	
7	Sandy Clay with 15 cm overlay of Sandy Loam	21-119 cm	-6.1, 342.5, 24.5, 0.72	.....	2, 36.9, 25.2, 20.9	No Collection, Slope	
15-27	Thin layers of ashes, bark and glass wool coated with sandy loam	sandy loam of 10-80	-0.29 to 18.4	46 to 149.8		No Collection	Borjesson et al, 1997a (Field Scale, Sweden)
After 10 yrs of cell completion	Soil Cover with 2.38 to 8.07 % organic content	40-60	21.69 to 39.85	2.5 to 7.19		No Collection	Jones and Nedwell, 1993 (Field Scale, UK)

a. Values are entered in the order of minimum, maximum, mean and median unless otherwise stated.

Table 3: Flux and Oxidation Capacity of Field Scale Research (Continued)

Age of Waste (yrs)	Cover Type	Cover Thickness	Flux (gm CH <sub>4</sub> /m <sup>2</sup> -d)	Oxidation (gm CH <sub>4</sub> /m <sup>2</sup> -d)	% Oxidation	Gas Collection System, Slope	Reference
3-5	Clay	1 m cover over waste	-8 to 575.1	.....	25.3 to 29.6	Active, Slope	Barlaz et al., 2004 (Field Scale, USA)
			0 to 0.34	.....	3.7 to 8.5	Active, Flat	
			0.03 to > 1000	.....	-0.2 to 75.5	Off, Slope	
	Shredded yard waste compost (35-50% brush)	0.15 m clay over waste, followed by 0.15 m tire chips and 1 m yard waste	-0.04 to 2.63	.....	19.3 to 20.8	Off, Flat	
			-1.73 to 1.33	.....	31.2 to 102.8	Active, Slope	
			-0.31 to 12.96	.....	16.4	Active, Flat	
			-0.32 to 0.53	.....	40.6 to 86.8	Off, Slope	
0-26	Ripe Sewage Sludge Compost (50%) + wood chips (50%)	0.9 m with 0.3 m course gravel	214.4	214.4	100	Active	Humer and Lechner, 2001 (Field Scale, Austria)
	MSW compost (Mechanical-Biological Compost)	0.9 m with 0.3 m course gravel	214.4	214.4	100	Active	
	Non-humic topsoil	Not specified	214.4	75.2	35	Active	
7	Sandy clay and sandy loam, thickly vegetated	45	-6.07, 330, <sup>a</sup> 21.6, 1.6		2, 63.9, <sup>c</sup> 25.5, 20.9	No Gas Collection	Abichou et al., 2006a (Field Scale, USA)
1	Sandy clay, daily cover	15 cm	-4.22, 596, <sup>a</sup> 53.6, 3.3		-8.3, 43.2, <sup>c</sup> 14.4, 10.7	No Gas Collection	

a. Values are entered in the order of minimum, maximum, mean and median.

Table 3: Flux and Oxidation Capacity of Field Scale Research (Continued)

Age of Waste (yrs)	Cover Type	Cover Thickness	Flux (gm CH <sub>4</sub> /m <sup>2</sup> -d)	% Oxidation	Gas Collection System, Slope	Reference
Not Specified	Soil (Clay 8.3±2.8, Silt 12.5 ± 3.6, fine sand 36.2± 2.8, coarse sand 39.9± 9.7)	40-100	43 ± 1.344, 0	49 ± 24	Active, Vertical Wells, Top Section	Borjesson et al, 2001 (Field Scale, Sweden)
			288± 336, 0.0074± 0.02, 185.6 ±121.4	41 ± 5, 23, -11 ± 10	Active, Vertical Wells, Slope section	
	Soil (Clay 2.4±1.7, Silt 5.2±3.9, fine sand 25.8± 3.7, coarse sand 65.3± 8.8)	30-80	0.0084± 0.026, 38.4± 93.6, 1.73 ± 1.68	94 ± 41, 20 ± 12, -11 ± 10	No Collection, Top Section	
			0.94± 1.92, -0.0012 ± 0.01	60 ± 27	No Collection, Slope Section	
4-6	Coarse sand + loam	40 cm coarse sand and 80 cm loam	-0.0084 to 10 (3.7 to 16.2 in hot spots)	40 ± 7	Active	Schuetz et al., 2003 (Field Scale, France)
4	Coarse sand	40 cm	37.8 ± 14.4 with maximum flux of 49.9	3.8 ± 1.3	Active	
26-28	Sandy-clay loam (53± 11% sand, 18 ± 17% silt and 29±16 clay)	1-2 m	61 to 78 , reduced by 40% after gas recovery	Summer 15.9±4.5, Fall 21.0±2.7, Spring 3.8±2.9 and Winter 6.8±0.9	Active	Chanton et al., 1999 (Field Scale, USA)
Not Specified	Sandy-clay loam (as above) and geomembrane	60% Sandy clay loam and 40% geomembrane	128 to 139, reduced by 75% after gas recovery		Active	

Table 3: Flux and Oxidation Capacity of Field Scale Research (Continued)

Age of Waste (yrs)	Cover Type	Cover Thickness	Flux (Kg CH <sub>4</sub> /d)	Oxidation (Kg CH <sub>4</sub> /d)	Gas Collection System	Reference
6-7	Organic soil, then geosynthetic clay liner and sand	30 cm organic soil	8.1	0.3	Active	Spokas et al., 2005 (Field Scale, France)
	Organic soil and Clay cover	30 cm organic soil and 1 m clay	49.4	2.1	Active	
5-6	Final Clay cover	Not Specified	Summer: 298.6 Winter: 56.0	Summer: 83.5 Winter: 9.8	active	
5-6	Thin clay Cover	Not Specified	Summer: 287.0 Winter: 15.0	Summer: 6.5 Winter: 2.3	active	
5-6			Summer: 5369	Summer: 7.1	Inactive	
12	Final Clay cover	Not Specified	0.01	4.0	Active, vertical wells	
	Final geomembrane cover		6.2	4.0	Active, horizontal wells	

## **Factors affecting Oxidation**

Certain properties of soils (water content, organic content, porosity), climatic conditions (temperature, air pressure), vegetation, depth of cover as well as some inhibiting factors can influence methane oxidation. A suitable cover that offers adequate nutrient supply and can influence the formation of colonies is also important in the process (Humer and Lechner, 1999). The factors generally affecting the degree of CH<sub>4</sub> oxidation are those that influence the microbial growth (Hilger and Barlaz, 2006).

### ***Water Content***

Water content plays an important role in CH<sub>4</sub> oxidation in landfill cover soils. Water has three major effects: i) offer the optimum environment for CH<sub>4</sub> oxidizing methanotrophic bacteria ii) influences the O<sub>2</sub> penetration to the soils iii) affects CH<sub>4</sub> transport in soils. Increase in water content decreases O<sub>2</sub> diffusion in the soil and thus decreases CH<sub>4</sub> oxidation. Water fills up the pores in the soil causes a seal in the cover and affects the CH<sub>4</sub> transport. This phenomenon can increase the pressure inside the landfill which influences the LFG to find the easiest path to travel and in effect, increase the CH<sub>4</sub> emissions (Abichou, 2004).

The optimal soil water content will be different in different types of soils. The optimum water content in the landfill cover was between 15.6 and 18.8% w/w (Boeckx et al., 1996; Christophersen et al., 2000), 15.7% (Czepiel et al., 1996a), 11% (Whalen et al., 1990), and 15 to 20% (Visvanathan et al., 1999). In laboratory column studies, composted organic materials (45% moisture content) performed better in oxidizing CH<sub>4</sub> than soil columns (17% moisture content). It was suggested that high CH<sub>4</sub> uptake is possible at high moisture contents as long as soil pore volumes are not water saturated (Humer and Lechner, 1999). It is also observed that a low moisture content of 6% produced negligible oxidation (Visvanathan et al., 1999). The critical factors seem to be the available soil pore volume for gas exchange at different moisture contents. CH<sub>4</sub> must reach to the methanotrophs by aqueous diffusion, which is much slower than the gaseous diffusion (Hilger and Humer, 2003).

“Isolation effect” of compost is beneficial for methane oxidation reported in the literature (Humer and Lencher, 1999). This effect is caused when the outer compost layer (10 – 20 cm) dries up. This desiccation induced a hydrophobic effect in the layer and a barrier is formed that prevents temperature loss in the lower compost layers. This confirms favorable

ambient conditions for the microorganisms that can grow in a moist and warm condition. The heat produced by microbial activity can be virtually stored over a longer term. Thus this “isolation effect” makes the system even more independent of low or varying outer temperature.

### ***Cover composition and organic content***

Generally, increased organic content in soils normally favors the oxidation rate due to high porosity and nutrients for methanotrophs (Christophersen et al., 2000). The compost must be matured with respiratory activity in 7 days less than 10 mg O<sub>2</sub>.g<sup>-1</sup> DM. It should have stable organic matter with low ammonium concentrations and no nitrite (Humer and Lechner, 2001). Two year old compost material can be a mature substrate which can offer a high pore volume and a good structural stability (Humer and Lechner, 2003). Even anaerobic CH<sub>4</sub> oxidation is reported in compost covers of landfill which is linked to sulfate reduction (Mancinelli, 1995).

### ***Porosity and Compaction***

Compacted landfill cover soil does not allow for optimal interaction of CH<sub>4</sub> and O<sub>2</sub> required for CH<sub>4</sub> oxidation. Limitations on physical transport become controlling factor in the field. The relative rates of CH<sub>4</sub> and O<sub>2</sub> transport to a certain depth is affected by rates of methanogenesis below and by O<sub>2</sub> from atmospheric sources above (Bogner et al, 1997). Methane oxidation mostly depends on the porosity and compaction of the cover materials.

Compost has high porosity which can provide a channel for oxygen penetration and a contact surface area to methanotrophs. Coarse grained soil is suitable for water infiltration. Thus soil texture, particle size and soil gas concentrations affect the CH<sub>4</sub> oxidation (Hilger and Humer, 2003).

### ***O<sub>2</sub> availability, Profile and Zone of Oxidation***

CH<sub>4</sub> oxidation is observed in an optimum zone of the landfill cover soils. The zone has optimum conditions for methanotrophic growth, CH<sub>4</sub> and O<sub>2</sub> ratio and retention time for proper oxidation (Abichou, 2004). The distributions of gas concentration in cover soils depend on diffusion, reaction, and gas flow (Visscher et al., 1999). High CH<sub>4</sub> concentration

increases CH<sub>4</sub> oxidation though higher CH<sub>4</sub> emission normally hinders the diffusion of O<sub>2</sub> into soil (Visscher et al., 2001). Variable depths of high oxidation activity have been reported in literature ranging from 3 cm to 90 cm (Czepiel et al., 1996a; Visvanathan et al., 1999; Borjesson and Svensson, 1997b; Kightley et al., 1995). The amount of infiltration influences the location of the oxidation horizon due to the different water or air-filled volumes (Humer and Lechner, 2003).

Czepiel et al (1996a) reported the maximum zone of oxidation at a depth of 5 cm to 10 cm in sandy-clay loam soil. For sewage sludge compost and MSW compost the maximum zone was reported at 40 cm and 90 cm, respectively (Humer and Lechner, 2001). Under certain conditions like a reduced supply of CH<sub>4</sub> or oxygen, the zone of oxidation may vertically proceed downward in the soil section (Humer and Lechner, 2001). The plant root can facilitate the transport of O<sub>2</sub> essential for CH<sub>4</sub> oxidation to greater depths (Humer and Lechner, 2003). The lower oxidation zone can be a result of relatively low LFG emission due to efficient gas extraction (Schuetz et al., 2003).

3% of oxygen concentration has been reported as a threshold value to oxidize CH<sub>4</sub> (Bender and Conrad, 1994; Czepiel et al., 1996a). Thus concentration of O<sub>2</sub> below the 3% can decrease the oxidation capacity of soil sharply though it has less effect above 3% concentration.

### ***Temperature***

Generally, CH<sub>4</sub> oxidation increases with temperature (Visscher et al., 2001). Though methanotrophic bacteria prefer a certain range of temperatures, warm weather proved to be preferable for the oxidation process. The soil temperature is the major factor of CH<sub>4</sub> oxidation, and accounts for 85% of the variability (Borjesson and Svensson, 1997b). CH<sub>4</sub> concentration in soil follows a seasonal pattern also with marked decrease in summer due to soil drying. Higher CH<sub>4</sub> is observed at night probably due to the inhibitory influence of low soil temperature on CH<sub>4</sub> oxidizing microorganisms (Borjesson and Svensson, 1997b). Extremely high (above 45°C) temperature is not suitable for oxidation process. High oxidation rate was observed up to temperature 36°C but no oxidation was reported when the temperature was increased to 45°C (Czepiel et al, 1996a). Oxidation rate is inhibited at 4°C about 70-80% of the rate of 18°C (Humer and Lechner, 2001). It is reported that optimum

temperatures for CH<sub>4</sub> oxidation are about 25 to 35° C (Borjesson and Svensson, 1997b). The optimal temperature decreases with increasing water content (Boeckx et al., 1996).

### ***Atmospheric Pressure***

A decline in air pressure can increase the pressure gradient between landfill and atmosphere. The pressure gradient can pump gas from the landfill. The pressure gradient can be increased when the vacuum of the system is reduced and thus will lead to increased CH<sub>4</sub> flux to the cover. A very strong negative relationship has been reported between the CH<sub>4</sub> emission and air pressure (Czepiel et al, 2003).

### ***Vegetation***

Vegetation is the regulatory requirement on all landfill covers in the USA (USEPA, 1991). Vegetation can affect the properties of soils such as its pH value, water content, and gas transport within their roots and thus can influence the CH<sub>4</sub> oxidation capacity of soil. Vegetation provides a channel for O<sub>2</sub> penetration and also serves as a channel for gas diffusion. It can also generate some microbiological environment due to enhanced nutrient supply and better moisture retention which are suitable for the oxidation process. Though it is reported that steady-state CH<sub>4</sub> consumption was similar in the presence and absence of grass (Hilger et al., 2000). CH<sub>4</sub> has influence on the growth of the vegetation that can be microbial-produced water and also from the high amount of nutrients present.

### ***Effects of NH<sub>4</sub> and NO<sub>3</sub>***

NH<sub>4</sub> has been reported as inhibitory factor in atmospheric CH<sub>4</sub> oxidation (Mosier et al., 1991). Vegetation in landfill cover can diminish the inhibitory effects of NH<sub>4</sub> at steady state (Hilger et al., 2000). Nitrate addition in landfill cover soil cause a significant increase in CH<sub>4</sub> uptake by fresh soil but showed no noticeable impact in grassed soil. It is reported that lime addition to fresh and grassed soil can raise the sample pH into the optimum range for methanotroph growth (Hilger et al 2000).

## Summary

Based on the emissions and oxidation studies, it is observed that CH<sub>4</sub> emissions from different landfills are highly variable due to types and thicknesses of covers (Abichou et al, 2006a; Abichou et al., 2006b; Humer and Lencher, 2001), status of gas collection system (Barlaz et al, 2004), season (Spokas et al., 2005), age of the landfill (Abichou et al, 2006a; Abichou et al., 2006b; Spokas et al., 2005) and different cover locations of the landfills (Barlaz et al, 2004; Borjesson et al, 2001). From field scale studies, it is observed that the biologically active covers like compost are most effective in CH<sub>4</sub> oxidation (Table 3). Gas collection system can reduce the CH<sub>4</sub> emissions significantly irrespective of the types of covers used. Among the several parameters influencing the CH<sub>4</sub> oxidation water content, temperature and porosity are most important factors. Those ensure environment for proper growth of methanotrophs and sufficient oxygen required for methane oxidation.

## Experimental Design and Methods

### Site Description

The Yolo County Central landfill is a non-hazardous solid waste landfill that first opened in 1975. The landfill site includes 292.2 hectares of land that comprises of 17 distinct solid waste management units and two leachate surface impoundments. The landfill is 3.2 km northeast of Davis, CA. The landfill unit where the CH<sub>4</sub> emissions tests were conducted contains refuse that was buried between November, 2003 and September, 2005 as follows: lift 1 was complete in November 2003, lift 2 was complete in November 2004, lift 3 was complete in August 2005, and lift 4 was complete in September 2005. Thus, the refuse was 3 to 5 years old during the field emissions test. The lift thicknesses were 10 ft, 15 ft, 10 ft, and 10 ft for lifts 1 to 4, respectively. One ft of soil cover was placed over lift 4 followed by a variety of test covers described in the Experimental Design. At the time of the emissions testing, an active gas collection system was in operation in this section of the landfill.

### Experimental Design

CH<sub>4</sub> emissions were measured in the field in January and November, 2006 using 1 m<sup>2</sup> static chambers. These two sampling events correspond to the rainy and dry seasons, respectively. Each sampling campaign lasted about two weeks during which time 4 to 5 emissions measurements were made with the LFG collection system at high vacuum, followed by a similar number of measurements with the system at low vacuum. No tests were conducted for at least 24 hrs after adjustment of the LFG system to allow for equilibration of pressure. Tests were conducted on 4 cover types including a soil control as described in Table 4. The variation in CH<sub>4</sub> concentration with depth was measured for most of the cover types with the LFG system at high and low vacuum. A layout of the test area is presented in Figures 1 and 2.

Table 4: Description of Covers Tested for CH<sub>4</sub> Emissions

Cover Types	Thicknesses (m)
Compost + Wood Chips	0.91, 0.31
Compost	0.91, 0.31
Green waste	0.91, 0.61, 0.31
Soil	0.31

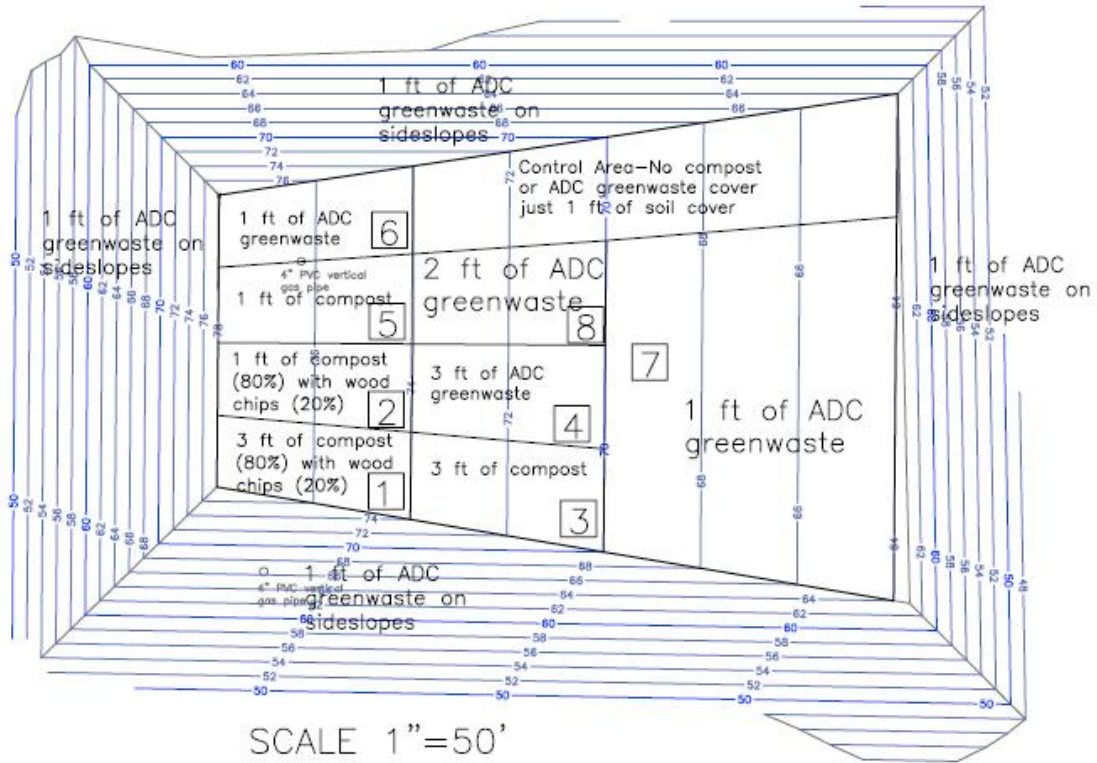


Figure 1: Landfill Plan Showing Different Landfill Covers in Place

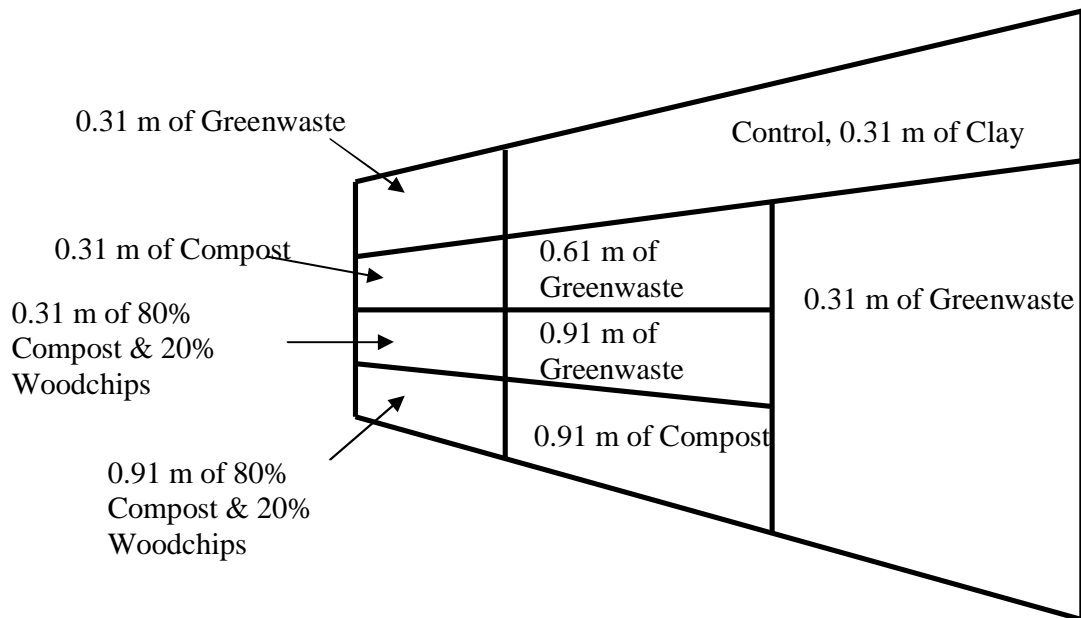


Figure 2: Schematic Diagram Showing Different Landfill Covers

Laboratory work was conducted in columns to evaluate several factors thought to influence CH<sub>4</sub> oxidation at the landfill. Eight columns were used to access the effects of

moisture addition and pulsed vs. continuous flow. For each phase of the experiment, four columns were operated with a continuous flow of CH<sub>4</sub>, and four columns were operated in a pulsed mode, receiving CH<sub>4</sub> for 8 days followed by 8 days with no CH<sub>4</sub> flow. Within each set of four columns, two were operated with moisture addition and two were operated without moisture addition to simulate the rainy and dry seasons, respectively. The assessment of the pulsed flow was intended to simulate the high and low vacuum of the LFG collection system. While a time interval of 24 to 48 hrs would have been a more appropriate simulation of field operation, this time interval was too short to allow for the column to reach steady state for purposes of measuring CH<sub>4</sub> oxidation. All treatments were conducted in duplicate.

Rainfall and evaporation data for Yolo County, CA were obtained from the California Irrigation Management Information System (CIMIS), California Department of Water Resources (DWR) to simulate the net infiltration and were used to determine the amount of water to be added to the columns (<http://www.cimis.water.ca.gov/cimis/data.jsp>). Average monthly rainfall was 5.6, 6.2, 9.8, 9.0 cm and average monthly evapotranspiration was 5.3, 3.9, 3.9, 5.7 cm for November, December, January and February, respectively. Water addition was calculated as average monthly rainfall minus monthly evapotranspiration for November through February (the rainy season) and surface run-off was assumed to be negligible. Thus, 59 mL/week of water was added to the moisture addition columns.

Columns were operated for 31 to 55 days at a series of increasing pressure gradients that were designed to represent the pressure gradients expected in the landfill. The pressure gradient in the field was estimated in work that was conducted at the University of Delaware. The maximum expected pressure gradient for the 0.61 m cover, comprised of one year old shredded green waste, was estimated and converted to a superficial velocity (Darcy velocity) that ranged from 10<sup>-5</sup> to 10<sup>-6</sup> m/s. A velocity of 10<sup>-5</sup> m/s translated to a LFG flow rate of 5 mL/min (294.3 gm/m<sup>2</sup>-day of CH<sub>4</sub>) for the 10.2 cm diameter column used in this study. The LFG feed rate of 5 mL/min was increased to 10 mL/min and 15 mL/min in phases two and three of the experiment. As explained in the results, limited testing was also conducted at 2.5 mL/min.

## Static Chamber Design

The static chamber consisted of a 1m<sup>2</sup> stainless steel collar and a lid (Fig. 3). The lid included a battery powered fan to mix the chamber headspace and an outlet fitted with a luer connection (Cole-Parmer EW-34507-34) so that a syringe could be used to collect samples for gas analysis. The luer adapter was held in place with a nut and washer. A 3-way male lock stopcock (Cole-Parmer EW-30600-25) was placed in the luer adapter to contain gas in the static chamber except during sampling. A 0.4 cm hole was drilled at the top of the chamber for the luer adapter. Weather stripping was used to form a gasket between the chamber and the top and the top and collar were connected with binder clips. The capacity of the fan to mix the chamber contents completely in less than 30 seconds was verified in preliminary work. This was appropriate given the 5 min sampling frequency.



Figure 3: Static Chamber Used for Emissions Measurements

## Chamber Tests

One chamber was used for each cover type and multiple tests were conducted with the same chamber to assess temporal variation. Chamber collars were left in place over the entire test program and the lids were moved between collars for each test. Prior to each field test program, vegetation inside each collar was trimmed to eliminate interference with the fan. In addition, the exact collar depth was measured on four sides and the average depth was used to calculate the chamber volume that is required to calculate the methane flux. To

begin a test, the lid was placed over the collar with the valve open to preclude a pressure increase. Once ready, the valve was closed which represents time zero. The first sample was collected after approximately two minutes to allow for complete mixing in the chamber. Samples were collected with a 60 mL plastic syringe inserted into the locking stopcock. The syringe was flushed with sample by withdrawing gas and injecting it back into the chamber, after which a 60 mL sample was collected and injected into evacuated 20 mL serum bottles sealed with butyl rubber stoppers and aluminum crimps. Samples were collected at approximately 5 min intervals for 25 minutes. Chamber tests were conducted by technicians employed by Yolo County after training by Dr. Barlaz and personnel from the University of Delaware.

### **Soil Column Construction and Assembly**

Laboratory-scale column experiments were conducted with aged green waste that is being used as a daily cover at the Yolo County Landfill. The green waste was about two years old at the time that it was used to fill the columns. Each PVC column was 10.2 cm in diameter and 0.91 m long. The bottom 0.15 m was filled with gravel, followed by 0.61 m of aged green waste and a 0.15 m headspace (Fig. 4). Columns were sealed at both ends with PVC caps. The (CH<sub>4</sub>+CO<sub>2</sub>) gas inlet was in the middle of the gravel layer, 0.075 m from the bottom of the column. Sample ports in the green waste were made from a compression fitting that was used to penetrate the column and a male hose barb that was used to connect tubing on the inside of the column. The tygon tube was terminated in the center of the column to facilitate even gas distribution. Gas sampling ports were located 0.05, 0.2, 0.36 and 0.51 m below the top of the compost. The air inlet was located 0.13 m below the top of column, about 0.025 m above the compost. Here too, compression fitting and male hose barb were used to connect tygon tube inside the column. The inlet had a 0.05 m extension inside the column for proper distribution of air. The objective was to provide atmospheric conditions above the green waste surface. Water was added using a compression fitting and male hose barb from the top of the PVC cap. A perforated tygon tube was connected to the fitting for distribution of water at the top of compost.

The synthetic LFG flow to the columns was supplied from a premixed gas cylinder containing 50% CH<sub>4</sub> and 50% CO<sub>2</sub>. The gas flow was regulated at 5, 10 and 15 mL/min in

phases 1, 2 and 3, respectively, using AALBORG gas mass flow controllers (Model GFC17, NY, USA). Air was supplied a rate of 50 mL/min in Phase 1 and 85 mL/min in phases 2 and 3 to provide oxygen in excess of the stoichiometric requirement. The air flow rate was controlled by Cole-Parmer flow meters (Model C-32003-04).

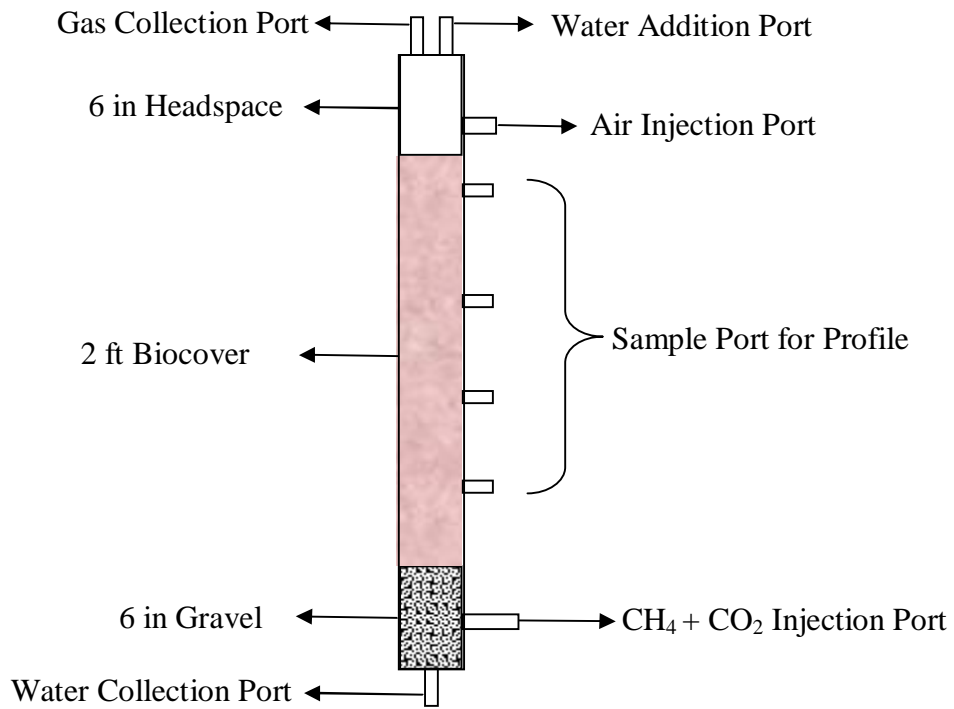


Figure 4: Picture (a) and Schematic (b) of the Column System to Study the Effect of Pressure Gradient, Moisture Addition and Pulsed Flow on Methane Oxidation

### Column Filling

The target dry density of  $0.7 \text{ gm/cm}^3$  was determined at the University of Delaware based on dry bulk density values of the samples obtained from Yolo County. This translates

to a wet density of  $1.01 \text{ gm/cm}^3$  based on the compost moisture content. The compost was mixed thoroughly in a drum before placement in the columns to reduce the heterogeneity of material in different columns. The compost was loosened properly and unwanted materials (e.g. glass, gravel etc) were removed to ensure uniformity in the compost. Gravel bought from LOWE'S was used to fill the lower 0.15 m of the columns. After covering the gravel with a layer of cheese cloth, compost was added in 0.08 m thick layers. Each layer was compacted with a rod (1.22 m long by 1.4 cm diameter) to ensure uniform packing and gas flow. A uniform load was applied by dropping the rod 30 to 40 times from approximately 7.6 cm above of the compost.

### **Column Operation and Monitoring**

All columns trials were conducted at  $22^\circ \pm 2^\circ\text{C}$ . The first phase was conducted for 55 days to determine the effect of pulsed flow. The following two phases were shorter (36 days and 31 days) as explained in the results.

The extent of  $\text{CH}_4$  oxidation was calculated from measurement of the  $\text{CH}_4$  volume entering and leaving a column.  $\text{CH}_4$  entering a column was recorded on the mass flow controllers that were calibrated for the LFG mixture. All of the gas exiting the column could not be collected so it was necessary to sample the exit gas and analyze composite samples. The exit gas flow rate was measured three times a day using a bubble meter. At each measurement time, the flow was measured twice and the measurements were repeated if the readings deviated by more than 2%. A gas sample was collected each time that the gas flow was measured and stored in a Tedlar® gas bag. In all cases, gas samples were collected at least 2 hours apart. To collect a gas sample, the column effluent line was connected to a gas bag for ten minutes. Gas samples from 2 days were combined in 1 bag for composition analysis. Gas samples were transferred from the Tedlar® bags to 20 mL evacuated serum bottles using a 60 mL syringe. The gas composition and average flow rate over this two day period were used to calculate the volume of  $\text{CH}_4$  in the effluent. For the columns receiving water, 59 mL water was added weekly and samples were always collected at least 24 hr after a water addition. For the pulsed flow columns, samples were not collected in the first 40 hr after the introduction of  $\text{CH}_4$  to allow for flushing of the column with at least 6 pore volumes of gas. Periodically, samples were also collected from the samples ports to determine the

depth of O<sub>2</sub> diffusion in the compost. Gas profile samples were always collected at least 18 hr before collection of an effluent gas sample.

## Analytical Methods

Gas concentrations were determined on an SRI gas chromatograph (GC) equipped with a CTR1 column, a thermal conductivity detector (TCD) and a flame ionization detector (FID). The temperature of the column oven, TCD and FID were 75, 102 and 144 °C, respectively. He was used as a carrier gas together with H<sub>2</sub> and air. The pressures were 0.207 N/mm<sup>2</sup> for the carrier gas, 0.131 N/mm<sup>2</sup> for H<sub>2</sub>, and 0.048 N/mm<sup>2</sup> for air during the analysis. The carrier gas flow rate (He) was 100 mL/min. Each gas sample was routed through the TCD followed by the FID. Thus, if a sample was too dilute to be detected by TCD, then it was detected by FID.

## Moisture and Solids Analysis

The moisture content of the compost was measured based on the moisture loss at 75 °C. Cellulose and hemicellulose were measured as described by Davis (1998). Briefly, a ground sample was subjected to a 72% (w/v) H<sub>2</sub>SO<sub>4</sub> hydrolysis, followed by a secondary hydrolysis in 3% (w/v) H<sub>2</sub>SO<sub>4</sub>. The hydrolyses converted cellulose and hemicellulose to their respective monomeric sugars, glucose, xylose, mannose, arabinose and galactose, that were quantified by HPLC equipped with a pulsed electrochemical detector. The glucose originated from cellulose and the other sugars from hemicellulose. The solids that remain after the hydrolyses contained acid-insoluble lignin, other organics and inorganics. The lignin concentration is calculated based on the loss on ignition at 550° C.

## Data Analysis

The % CH<sub>4</sub> oxidized in the laboratory columns were calculated as:

$$\% \text{ CH}_4 \text{ oxidized} = (\text{CH}_4 \text{ in} - \text{CH}_4 \text{ out}) / (\text{CH}_4 \text{ in}) \quad (5)$$

The CH<sub>4</sub> flux from a soil cover, as measured by the static chamber test, was calculated using the following equation:

$$\text{Flux} = V/A * \Delta c / \Delta t \quad (6)$$

Where, V is the static chamber volume (m<sup>3</sup>), A is the surface area enclosed by the chamber (m<sup>2</sup>) and  $\Delta c / \Delta t$  is the slope of a plot of CH<sub>4</sub> concentration (ppmv) versus time (min). Flux data were then converted to a mass emission rate by using the ideal gas law. A non-zero CH<sub>4</sub> flux was only reported if the slope ( $\Delta c / \Delta t$ ) was statistically different from zero

( $p < 0.05$ ). Otherwise, a flux of zero was reported. The Regression Analysis add-in of MS Excel was used to calculate the probabilities. The correlation coefficients ( $r^2$ ) for static chamber tests were generally above 0.95.

## Results

The laboratory columns were operated for about 140 days to evaluate the CH<sub>4</sub> oxidation potential of the two year old green waste. The results of these tests are presented first, followed by results of the landfill cover emissions testing program.

The CH<sub>4</sub> oxidation rates for each column are presented in Tables 5 to 8 for each LFG feed rate. The data are plotted in Figures 5 and 6 for the continuous and pulsed flow columns, respectively. Average CH<sub>4</sub> uptake for each phase of the experiment is presented in Table 9, as the % of the inlet CH<sub>4</sub> that was oxidized, and in Table 10 as the gm CH<sub>4</sub> oxidized/m<sup>2</sup>-day. Data for column 4 have been excluded due to evidence of leakage. In some cases, negative values are reported which implies CH<sub>4</sub> production. The negative values are in general low and random and likely reflect a combination of experimental errors in measuring zero oxidation. In general, there was high variability between columns and limited reproducibility. As such, more general observations are presented with the use of statistical tests only where judged appropriate. All columns were operated in continuous flow mode after 55 days because pulsed mode did not appear to have any effect on CH<sub>4</sub> oxidation at the 5 mL/min flow rate. The final phase of testing, at a feed rate of 2.5 mL/min was added at the end of the experiment based on the results.

### Effect of Gradient

The effects of pressure gradient on CH<sub>4</sub> oxidation were assessed by measuring CH<sub>4</sub> oxidation at flow rates of 5, 10 and 15 mL LFG/min. These flow rates correspond to CH<sub>4</sub> fluxes of 294.3, 588.7 and 883.01 gm/m<sup>2</sup>-day. As presented in Table 9 and Figures 5 and 6, the fraction of the feed CH<sub>4</sub> that was oxidized decreased in each column as the CH<sub>4</sub> flow rate increased. While the average % CH<sub>4</sub> oxidation ranged from 27 to 69% at the lowest flow rate, this decreased substantially at the highest flow rate when only column 2 exhibited CH<sub>4</sub> oxidation above 67%. Although columns 1 and 2 were replicates, almost no CH<sub>4</sub> oxidation was measured in column 1 at 10 or 15 mL/min.

CH<sub>4</sub> uptake was also expressed as the gm of CH<sub>4</sub> uptake per m<sup>2</sup>-day which is consistent with the manner in which CH<sub>4</sub> emissions data are typically expressed. With the possible exception of columns 2 and 6, average CH<sub>4</sub> uptake also decreased as the pressure gradient increased. The decrease in % CH<sub>4</sub> oxidation suggests that the amount of CH<sub>4</sub> fed

exceeded the oxidation capacity of the system, presumably because there was insufficient retention time in regions where CH<sub>4</sub> and O<sub>2</sub> mixed. Column 2 exhibited the most CH<sub>4</sub> uptake and uptake actually increased with gas feed rate while it was more variable in column 6. Unfortunately, columns 1 and 5, which were replicates of 2 and 6, exhibited decreased CH<sub>4</sub> uptake with increasing gas flow rate.

Based on the results of the 5, 10, and 15 mL/min flow rates, limited work was also conducted at 2.5 mL/min. After decreasing the flow rate from 15 mL/min to 2.5 mL/min, the fraction of CH<sub>4</sub> oxidized increased in the no water addition columns (1, 2, 5, 6), suggesting 1) that the lower pressure gradient increased oxidation and 2) some inhibition due to moisture addition. The effect of moisture addition is discussed below. The behavior of column 2 is surprising as the mass of CH<sub>4</sub> oxidized decreased substantially at the lowest gas feed rate. One explanation for this would be preferential flow of some fraction of the gas.

The effect of the pressure gradient on the gas profile in each column is presented in Figure 7 and the complete data set is presented in Appendix A. The profile data do not suggest an effect attributable to pressure gradient, suggesting that oxygen penetration was controlled by diffusion.

Table 5: Methane Oxidation (%) for 5 mL/min of (CH<sub>4</sub>+CO<sub>2</sub>) and 50 mL/min Air in Laboratory Columns

	Pulsed CH <sub>4</sub> Flow			Continuous CH <sub>4</sub> Flow			
	- Water Addition		+ Water Addition	- Water Addition		+ Water Addition	
Column	1	2	3	5	6	7	8
Day							
4.11	33.8	95.8	22.6	15.4	ND*	-3.5	87.7
6.26	23.9	98.9	53.8	35.6	ND	15.4	94.5
8.53	47.2	91.1	43.4	90.2	ND	13.2	90.5
10.5				36.1	ND	9.3	96.0
12.11				33.0	ND	34.3	66.5
14.5				74.5	60.0	77.8	91.9
16.5				24.6	73.1	13.9	79.0
18.2	71.8	96.5	49.7	20.6	81.8	5.4	93.5
20.2	32.4	94.9	51.4	62.4	51.2	52.7	100.0
22.5	29.5	91.1	13.5	23.1	63.3	61.5	81.9
24.3	33.9	92.0	11.5	34.1	72.5	51.9	79.5
26.3				23.0	55.0	45.8	52.9
28.4				17.5	44.8	25.7	66.6
30.4				26.6	57.0	61.5	73.8
32.2				18.9	50.6	53.5	38.5
34.24				100.0	30.5	100.0	71.1
36.06				32.3	43.4	57.1	66.7
38.27	56.4	93.9	-13.0	15.2	43.4	57.1	66.7
40.18	26.5	90.3	-0.1	-10.9	43.7	55.2	68.3
42.31				9.3	40.3	56.7	62.7
44.27				16.9	38.3	54.7	61.9
46.27				17.3	37.2	54.4	61.5
48.32				13.9	47.6	49.3	76.4
50.26	63.8	90.9	35.1	20.9	50.1	25.0	17.5
52.29	34.6	87.3	22.3	25.6	62.9	40.2	29.6
54.29	14.5	83.5	31.2	14.1	54.4	34.6	-7.1

\*ND = No column 6 data due to problems with mass flow controller

Table 6: Methane Oxidation (%) for 10 mL/min of (CH<sub>4</sub>+CO<sub>2</sub>) as well as 50 mL/min and 85 mL/min Air in Laboratory Columns

	Continuous CH <sub>4</sub> Flow						
	- Water Addition		+ Water Addition	- Water Addition		+ Water Addition	
Column	1	2	3	5	6	7	8
Day							
4.35	8.3	74.2	18.6	-1.5	47.4	10.3	-6.0
6.34	15.8	75.7	0.2	8.8	50.8	12.8	-4.1
8.61	-3.4	70.6	5.5	-0.4	41.1	7.6	-8.4
12.61	21.2	76.5	24.6	2.4	32.0	12.2	18.3
14.64	17.7	72.2	2.4	1.3	37.3	6.6	0.5
16.7	4.0	71.3	21.6	19.8	31.1	11.4	0.6
18.6	11.4	75.4	19.7	18.6	34.5	14.6	11.6
22.6	-2.6	67.7	-2.7	23.7	20.5	5.2	-6.8
24.6	-2.2	71.8	25.9	16.2	24.2	20.4	19.3
26.7*	-13.8	70.1	-1.0	-11.6	25.2	3.5	-16.7
28.6	-8.3	72.0	22.3	-10.0	33.9	-1.5	-6.5
30.7	-15.0	67.1	-8.7	-9.2	19.1	-4.9	-8.0
32.6	0.2	70.0	11.9	7.2	20.5	-5.1	-18.4
34.6	0.6	74.4	4.0	-2.8	26.0	14.7	-6.8
36.4	-7.9	71.7	-3.2	-6.9	27.1	-2.0	-8.2

\* Air flow rate was changed from 50 mL/min to 85 mL/min on this day

Table 7: Methane Oxidation (%) for 15 mL/min of (CH<sub>4</sub>+CO<sub>2</sub>) and 85 mL/min Air in Laboratory Columns

	Continuous CH <sub>4</sub> Flow						
	- Water Addition		+ Water Addition	- Water Addition		+ Water Addition	
Column	1	2	3	5	6	7	8
Day							
3.42	5.59	69.34	17.26	4.0	21.1	10.0	63.8
5.33	-7.59	68.1	4.6	-4.7	14.5	0.6	58.0
7.4	0.8	75.2	1.2	15.0	25.1	-4.9	23.8
9.35	2.4	66.5	-2.8	-6.0	22.3	-4.5	-9.2
11.37	2.8	65.4	12.0	9.1	14.2	-1.8	-17.0
13.3	-11.3	63.4	-5.7	-13.8	6.9	-11.1	-17.1
15.3	6.3	68.6	-2.1	0.9	29.2	-8.6	-13.9
17.3	4.0	64.4	3.1	-1.9	8.4	-3.7	-13.0
19.4	-8.5	65.2	-8.4	-11.4	7.7	-9.7	-17.1
21.38	-5.8	67.3	4.6	-7.4	10.5	-6.7	-2.8
25.34	18.9	64.7	22.3	-7.5	6.0	2.4	0.5
27.36	-18.4	62.9	-16.6	-17.5	6.3	-14.9	-21.3
29.3	-1.4	70.5	15.3	-13.6	11.9	3.0	8.8
31.3	1.6	65.7	13.3	-6.2	19.6	11.8	6.2

Table 8: Methane Oxidation (%) for 2.5 mL/min of (CH<sub>4</sub>+CO<sub>2</sub>) and 50 mL/min Air in Laboratory Columns

	Continuous CH <sub>4</sub> Flow						
	- Water Addition		+ Water Addition	- Water Addition		+ Water Addition	
Column	1	2	3	5	6	7	8
Day							
4.5	17.2	74.8	13.4	22.4	63.6	2.7	-22.7
6.4	46.2	83.4	37.7	47.6	77.8	35.8	7.6
8.2	27.3	80.0	16.3	32.5	66.8	13.4	-13.2
10.4	26.5	78.1	10.4	28.9	68.6	20.7	3.2
12.4	40.6	75.2	28.9	37.3	52.6	-12.8	-17.3
16.4	33.7	77.4	ND*	ND	ND	-6.6	-21.2
18.4	33.1	76.4	ND	ND	ND	2.9	-13.7

\*Columns were taken apart for moisture analysis

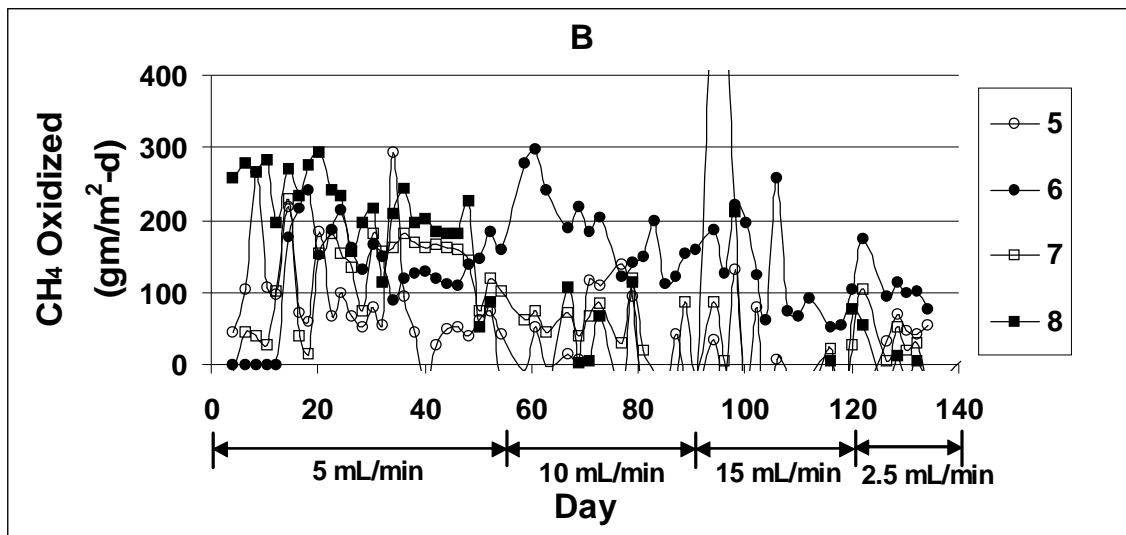
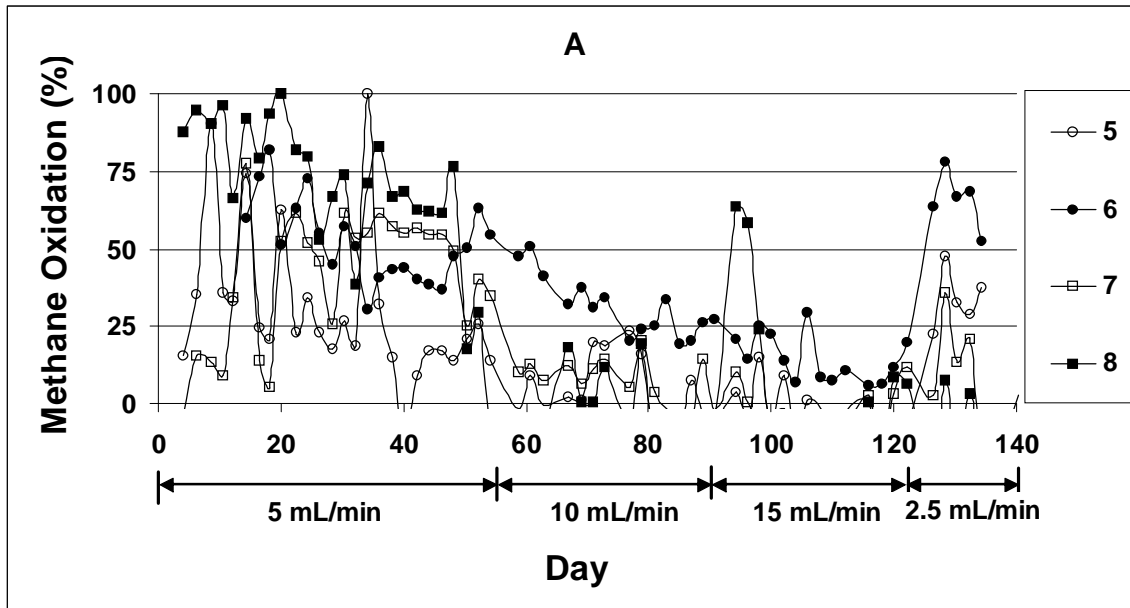


Figure 5: Methane Oxidation in Continuous Flow Laboratory Columns A) Expressed as % oxidation and B) Expressed as a methane uptake rate. Columns 5, 6 - no water addition; columns 7, 8 - water addition

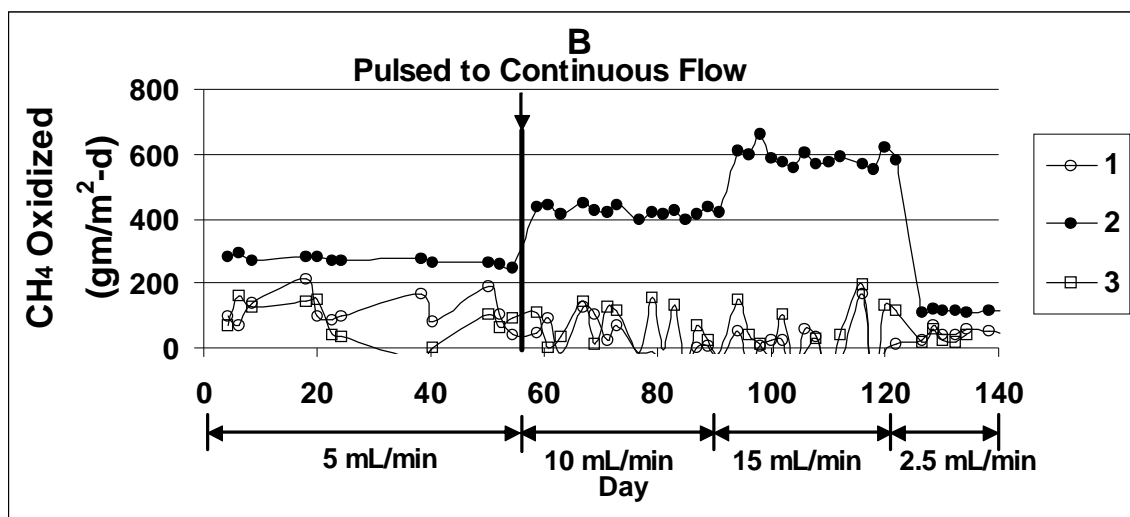
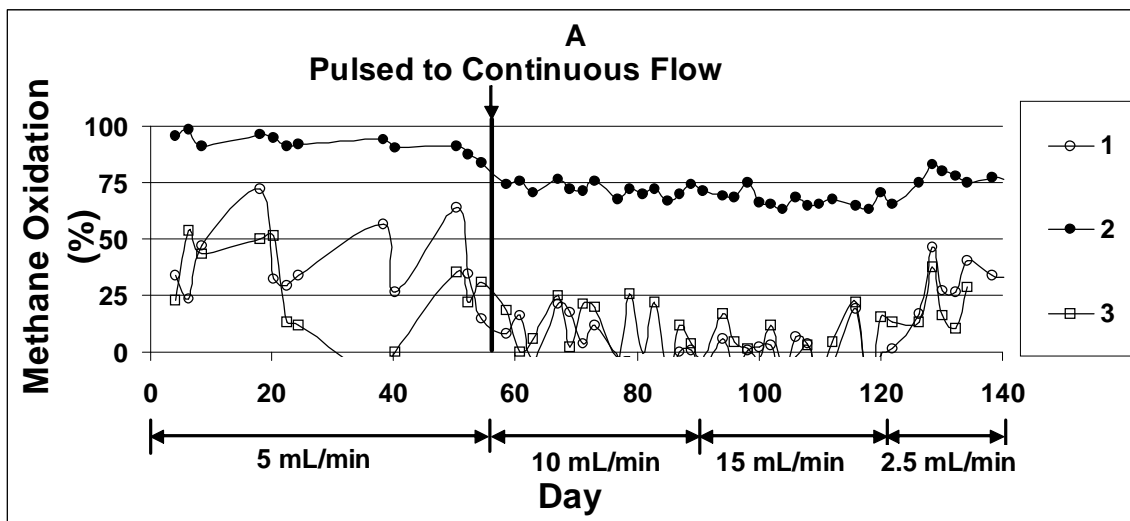


Figure 6: Methane Oxidation in Pulsed Flow Columns A) Expressed as % oxidation and B) Expressed as methane uptake rate. Columns 1, 2 - no water addition; columns 3 - water addition

Table 9: Average CH<sub>4</sub> Oxidation at Each Feed Gas Flow Rate (%)

Gas Flow (mL/min)		% CH <sub>4</sub> Oxidized							
		*Pulsed Methane Flow				Continuous Methane Flow			
		- Water Addition		+ Water Addition		- Water Addition		+ Water Addition	
		1	2	3	5	6	7	8	
5	Average	39.0	92.2	26.8	30.4	52.3	40.9	68.6	
	s.d.	17.2	4.2	21.3	25.0	13.1	21.3	25.5	
10	Average	1.7	72.0	9.4	3.7	31.4	7.1	-2.7	
	S.d.	11.2	2.8	11.8	11.5	9.7	7.8	11.2	
15	Average	-0.6	67.4	2.1	-1.0	16.6	-3.8	6.5	
	S.d.	6.7	3.6	8.3	9.3	8.2	6.4	33.4	
2.5	Average	32.1	77.9	21.3	33.7	65.9	8.0	-11.1	
	S.d.	9.6	3.0	11.6	9.4	9.1	16.7	11.8	

\*Columns were operated in pulsed mode at 5 mL/min. At other phases columns 1, 2 and 3 were operated in continuous mode.

Table 10: Average CH<sub>4</sub> Oxidized at Each Feed Gas Flow Rate [gm-CH<sub>4</sub>/(m<sup>2</sup>-d)]

Gas Flow (mL/min)		gm CH <sub>4</sub> /(m <sup>2</sup> -d) Oxidized							
		*Pulsed Methane Flow				Continuous Methane Flow			
		- Water Addition		+ Water Addition		- Water Addition		+ Water Addition	
		1	2	3	5	6	7	8	
5	Average	114.9	271.4	78.8	89.5	124.3	120.3	202.0	
	S.d.	50.6	12.4	62.6	73.6	70.9	62.8	75.1	
10	Average	10.3	424.1	55.4	21.8	184.8	41.6	-15.6	
	S.d.	65.9	16.4	69.3	68.0	56.9	45.7	65.8	
15	Average	-6.7	591.2	36.6	-38.4	128.4	-24.0	31.4	
	S.d.	80.6	28.9	96.4	80.6	67.6	67.9	241.5	
2.5	Average	47.2	114.6	31.39	49.65	96.9	11.8	-16.3	
	S.d.	14.14	33.2	4.42	13.9	13.4	24.5	17.4	

\*Columns were operated in pulsed mode at 5 mL/min. At other phases columns 1, 2 and 3 were operated in continuous mode.

### Effect of Infiltration

Columns 3, 7 and 8 received weekly moisture additions while the remaining columns did not. As CH<sub>4</sub> oxidation was observed in many columns, the initial compost moisture content was clearly sufficient to support CH<sub>4</sub> oxidation.

The profile data are presented in Figure 7 and are divided by columns that did and did not receive a moisture addition in Table 11. These data show that the O<sub>2</sub> concentration in all columns was comparable after 4 days. Thereafter, the O<sub>2</sub> concentration at each level was

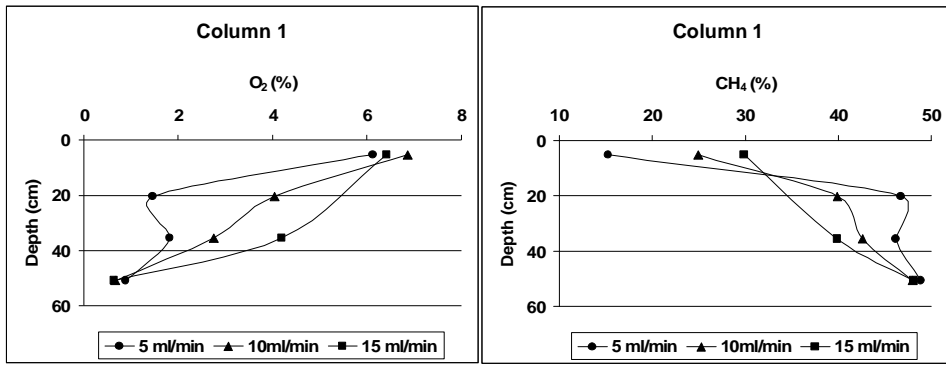
lower in the columns that received moisture addition. Similarly the methane concentration was higher at each level. Apparently, the addition of moisture filled some of the compost pore space, thus decreasing the potential for gaseous diffusion. The added moisture may also have stimulated decomposition of the compost which would increase O<sub>2</sub> uptake by the compost. The decrease in O<sub>2</sub> concentration would suggest inhibition of CH<sub>4</sub> oxidation based on limited O<sub>2</sub> availability although for the 5, 10 and 15 mL/min tests, there is too much variability in the CH<sub>4</sub> uptake data to make a definitive statement. The effect appears more clearly at the 2.5 mL/min test where methane oxidation was consistently lower in the columns that received moisture.

Table 11: Average O<sub>2</sub> and CH<sub>4</sub> Concentration Profiles in Moisture Addition and No Moisture Addition Columns

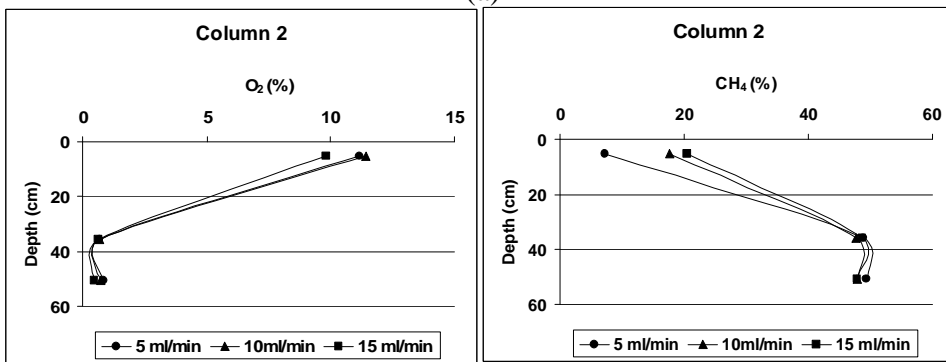
Depth Below Top of the Compost (cm)	O <sub>2</sub>			CH <sub>4</sub>		
	Avg. in Moisture Addition Columns (SD)	Avg. in No Moisture Addition Columns (SD)	p*	Avg. in Moisture Addition Columns (SD)	Avg. in No Moisture Addition Columns (SD)	p*
<b>Day 4: 50 ml/min Air + 5 ml/min LFG</b>						
5.1	9.8 (3.2)	11.5 (1.0)	0.46	18.8 (9.6)	13.6 (7.0)	0.49
20.3	2.5 (1.4)	2.2 (0.7)	0.74	39.1(9.5)	38.9 (6.5)	0.97
35.6	1.5 (0.3)	1.6 (0.5)	0.67	45.9 (2.6)	46.4 (0.2)	0.77
50.8	1.2 (0.3)	1.2 (0.1)	0.87	48.4 (2.0)	48.8 (0.8)	0.77
<b>Day 55: 50 ml/min Air + 5 ml/min LFG</b>						
5.1	0.7 (0.1)	8.2 (2.4)	0.009	50.3 (0.1)	11.8 (4.6)	0.00
20.3	0.6 (0.03)	3.7 (2.9)	0.21	50.2(0.3)	33.7 (13.3)	0.16
35.6	0.7 (0.2)	1.7 (1.4)	0.27	49.8 (0.3)	44.1 (6.1)	0.15
50.8	0.6 (0.1)	1.9 (2.3)	0.33	50.1 (0.3)	45.5 (6.9)	0.28
<b>Day 90: 85 ml/min Air + 10 ml/min LFG</b>						
5.1	0.8 (0.1)	7.9 (2.3)	0.009	48.4 (0.2)	22.8 (3.5)	0.001
20.3	0.7 (0.02)	3.5 (0.5)	0.01	48.7 (0.2)	41.5 (1.4)	0.01
35.6	0.7 (0.02)	1.2 (1.1)	0.42	48.1 (0.04)	46.5(2.6)	0.31
50.8	0.7 (0.1)	0.7 (0.03)	0.73	48.3 (0.4)	48.1 (0.2)	0.41
<b>Day 121: 85 ml/min Air + 15 ml/min LFG</b>						
5.1	0.6 (0.2)	6.9 (2.1)	0.01	49.2 (0.3)	26.1 (4.5)	0.002
20.3	0.6 (0.02)	5.0 (3.7)	0.33	49.1 (0.2)	40.6 (4.7)	0.24
35.6	0.6 (0.1)	1.9 (1.7)	0.22	48.8 (0.2)	45.6 (4.1)	0.22
50.8	0.6 (0.2)	3.3 (5.4)	0.39	48.3 (0.4)	41.6 (13.2)	0.38

\* The probability that the mean O<sub>2</sub> or CH<sub>4</sub> concentration is statistically similar between columns that did and did not receive a water addition.

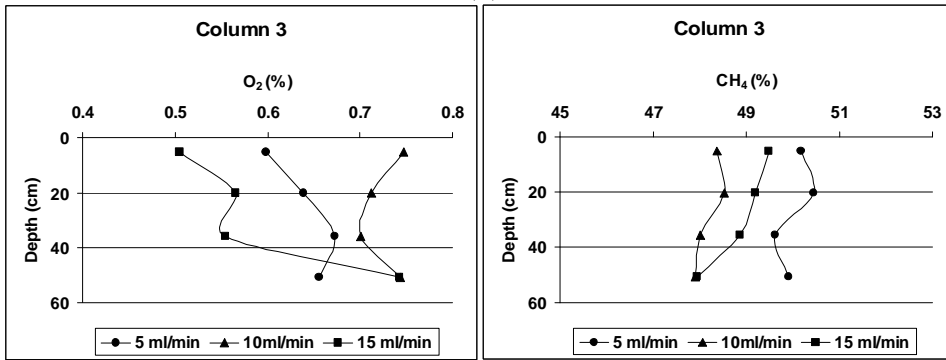
Figure 7: O<sub>2</sub> and CH<sub>4</sub> Profiles. Profiles were collected on days 55, 90, and 121 for 5, 10, and 15 ml/min flow rates, respectively. Note that the X-axis scale varies between plots.



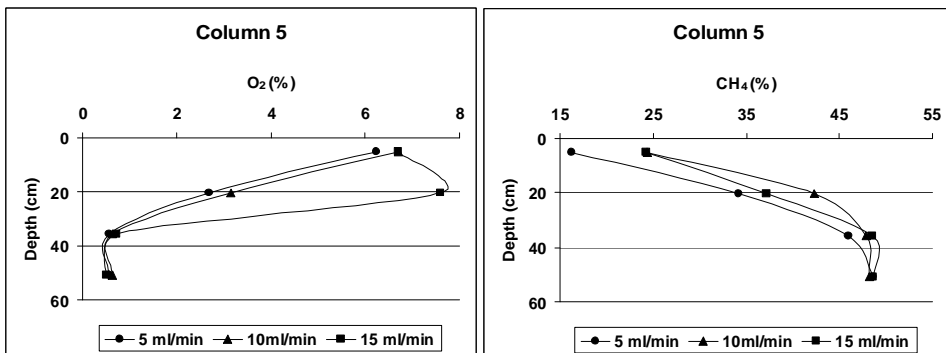
(a)



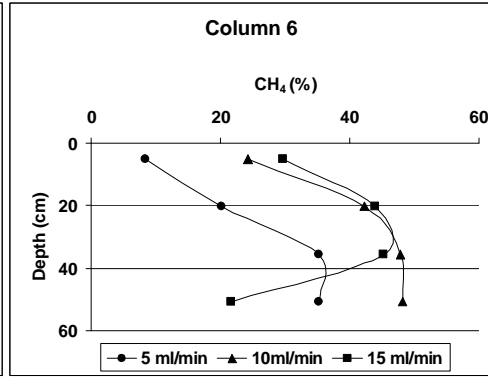
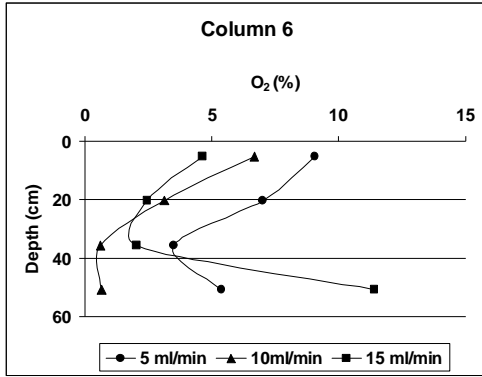
(b)



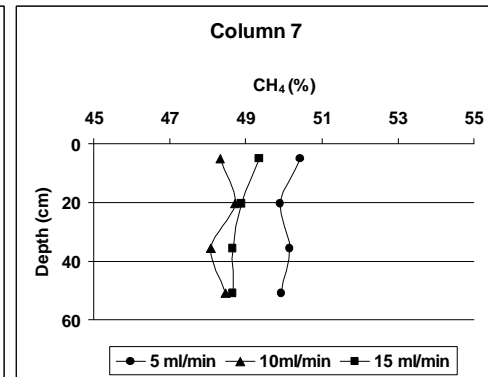
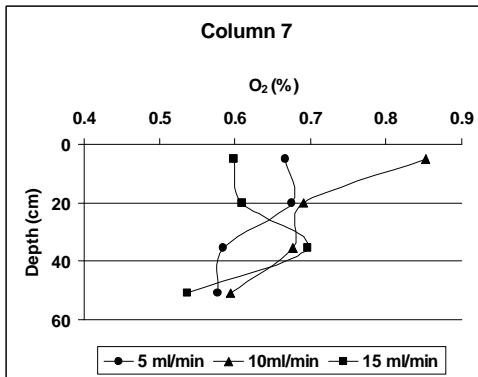
(c)



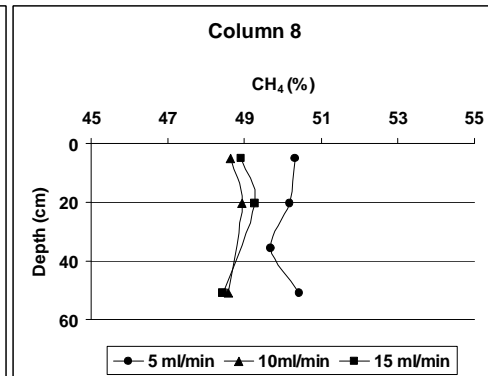
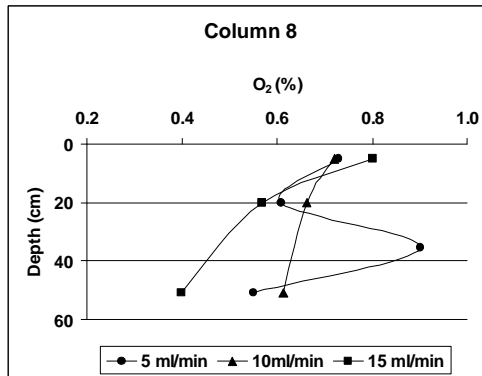
(d)



(e)



(f)



(g)

The moisture contents of the columns at the end of the experiment are summarized in Tables 12 and 13 and profiles with depth are presented in Figure 8. The total volume of water added to columns 3, 7 and 8 over the experimental period was 1.18 L per column. Assuming initial compost moisture content of 31.2%, this volume of water would have increased the compost moisture content to 44.35% if the moisture was spread evenly throughout the column, or to 64.6% if the moisture wetted the top 25% of the compost only. These values do not include evaporative losses or the production of water as an end product of CH<sub>4</sub> oxidation. The volume of water produced from the cumulative methane oxidized in each column ranged from 172 mL to 960 mL (Table 12). As evidenced by the moisture content at the end of the experiments, moisture addition resulted in increased compost moisture content. In addition, standing water was measured above the compost in the water addition columns at takedown (Table 12). This pattern is also illustrated by the profile data. In the columns that did not receive moisture addition, an increase in the moisture content was measured at the mid-depths (20 to 40 cm). The likely explanation for this is that the mid-depths are where there was maximum overlap of CH<sub>4</sub> and O<sub>2</sub> and subsequent methane oxidation. The higher moisture is consistent with water as an end product of methane oxidation. This same observation was reported by Hilger et al. (2000).

Table 12: Moisture Contents, Water Produced and Water Added in Columns

Column	Depth Below Top of the Compost (cm)	Moisture Contents (%)	Water Accumulated Above Compost (mL)	Water Produced from Oxidation (mL)	Water Added (mL)
1	5.1	35.2		210	
	20.3	40.5			
	35.6	39.3			
	50.8	38.2			
2	5.1	34.7		960	
	20.3	39.1			
	35.6	40.1			
	50.8	39.5			
3	5.1	44.5	100	170	1180
	20.3	40.0			
	35.6	40.8			
	50.8	31.8			
5	5.1	29.8		140	
	20.3	31.3			
	35.6	32.3			
	50.8	29.5			
6	5.1	31.0		340	
	20.3	32.6			
	35.6	32.0			
	50.8	30.7			
7	5.1	51.6	350	172	1180
	20.3	43.3			
	35.6	39.2			
	50.8	38.3			
8	5.1	53.9	270	240	1180
	20.3	45.8			
	35.6	40.8			
	50.8	39.7			

Table 13: Average Moisture Contents in Moisture Addition and No Moisture Addition Columns

Depth Below Top of the Compost (cm)	Avg. Moisture Content in No Water Addition Columns (SD)	Avg. Moisture Content in Water Addition Columns (SD)	p*
5.1	32.7 (2.7)	50.0 (4.9)	0.013
20.3	35.8 (4.6)	43.1 (2.9)	0.054
35.6	35.9 (4.4)	40.3 (0.9)	0.137
50.8	34.5 (5.1)	36.6 (4.2)	0.574

\* The probability that the mean moisture content is statistically similar between columns that did and did not receive a water addition

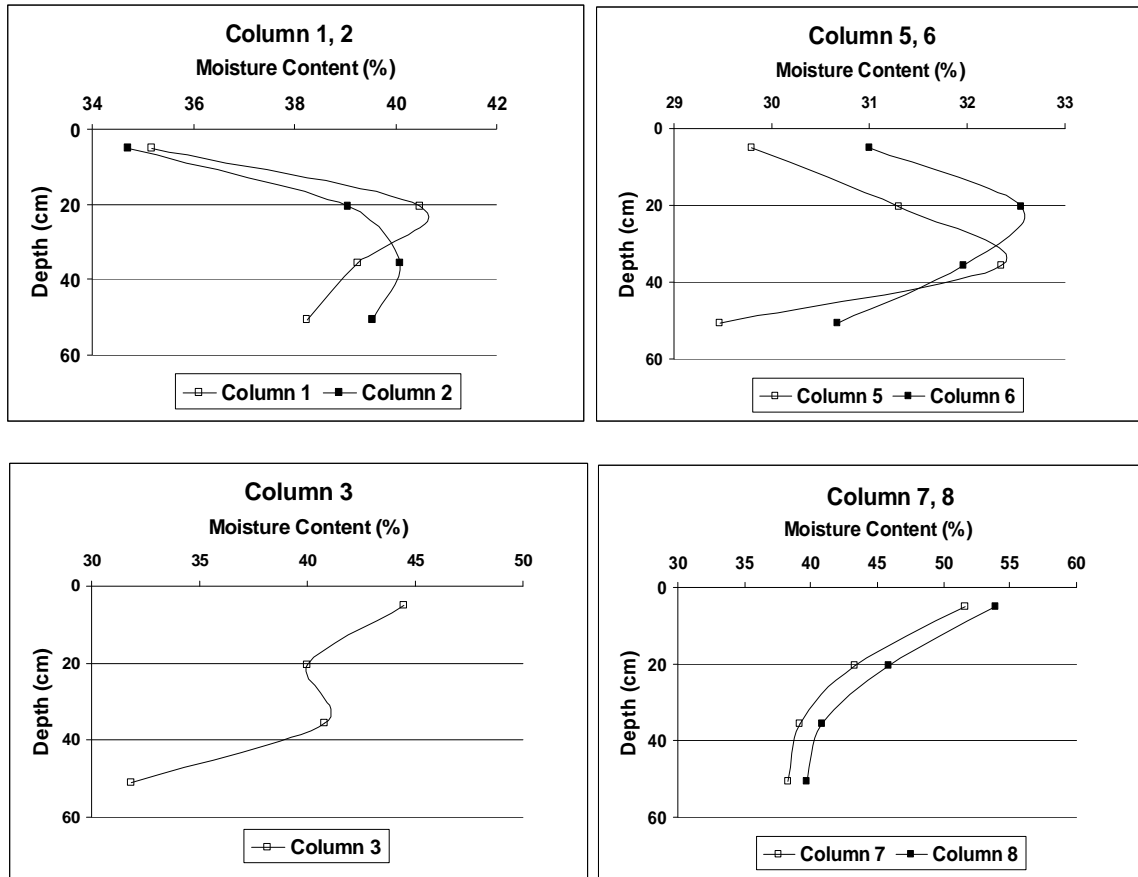


Figure 8: Moisture Content Profiles in the Columns at the End of the Experiment. Columns 3, 7 and 8 received moisture addition.

### Effect of Pulsed Flow

Pulsed flow was evaluated to simulate the field operation in which the cover would be exposed to little or no CH<sub>4</sub> while the gas collection system was operated at full vacuum and

increased CH<sub>4</sub> when the system was operated at low vacuum. The effect of pulsed flow was discontinued after the first phase of the experiment at a gas flow rate of 5 mL/min. Thereafter, columns 3, 7 and 8 were all replicates as were columns 1, 2, 5 and 6.

The average CH<sub>4</sub> uptake data do not suggest any effect associated with pulsed flow (Table 5, Figures 5, 6). Even when the methanotrophic bacteria are deprived of CH<sub>4</sub> for 8 days, their overall CH<sub>4</sub> uptake was comparable to that in the columns with a continuous feed of CH<sub>4</sub>. Interestingly, pulsed flow column 2 had the highest CH<sub>4</sub> uptake of any column.

### **Result Variability**

The oxidation results were highly variable among the columns. In the first phase of the experiment, there were 4 sets of columns with 2 replicates in each set. Columns 1 and 2 received pulsed flow with no water addition, columns 3 and 4 received pulsed flow with water addition, columns 5 and 6 received continuous flow with no water addition and column 7 and 8 received continuous flow with water addition. As there was no effect of the pulsed flow observed and the results were not reproducible between replicate columns, the pulsed flow columns were converted to continuous flow columns to increase replication. Thus there were 4 replicate columns with no water addition and 4 replicate columns with water addition in phase 2, 3 and 4. Unfortunately, the results were not reproducible. While a definite explanation is unclear, potential explanations for the variability are discussed in this section.

One possible explanation for the observed variability is compost heterogeneity. This could include differences in material composition and pore structure. Variability in compaction could affect the porosity of the compost in each column. Though procedures were used to compact the compost uniformly, it is possible that the procedures were inadequate. Lack of uniformity in pore structure could lead to preferential gas flow which could influence the zone of oxidation where the CH<sub>4</sub> and O<sub>2</sub> react. To minimize preferential flow through the walls caulk with tygon tubes was used at different heights of the columns. It is observed at the end of the experiment that the caulked tube was not in good condition and its condition varied among columns. It is possible that the caulk was not equally effective in all columns.

The target porosity in the columns was 0.3 which is higher than reported field and laboratory values for biocovers (Humer and Lechner, 1999., Humer and Lechner, 2001, Stein and Hettiaratchi, 2000). While the effect of too much compaction is not clear, it could have been a factor in the results. It is also possible that some columns were over-compacted and some were under-compacted. Variability in compaction would affect the diffusion of oxygen which would influence the results.

The gas was introduced to the columns through a gravel pack at the bottom of the column (Fig. 4). It is possible that the distribution of gas from gravel to the bottom of the compost was not even. As the gravel was not carefully graded, the non-uniform size of the gravel might affect the flow path of the gas mixture.

Although there is a clear indication in this experiment of high oxidation capacity of the compost, the results are not useful in evaluating the effect of pulsed flow. The data do suggest that too much moisture addition can be inhibitory as would be expected.

### **Compost Quality**

The covers were characterized to evaluate whether there was evidence of decomposition over about a year. Covers were sampled about two weeks apart in late January and February, 2006 and again in April, 2007. Solids composition data as well as biological indicators of cover stability are presented in Tables 14 and 15. For the initial sampling in 2006, samples collected from covers of the same type but varying thickness should be replicates.

Based on the initial sampling, there was considerable variability in several parameters, which serves to emphasize the heterogeneity of the cover materials. For example, the organic content and C:N ratio varied between the 0.31 and 0.91 m green waste covers. According to the Woods End Laboratory, materials with % C losses per day of 0.2 to 0.8 and 0.8 to 1.5 are classified as “medium to high stable” and “medium stable,” respectively. The higher CO<sub>2</sub> production in the green waste was expected as it is a fresher material. However, the Woods End Laboratory also suggests that finished compost has a C:N of <17, suggesting that the 0.31 m green waste sample was more decomposed than both the compost and 0.91 m green waste samples (Table 14).

The solids composition should not differ as function of cover thickness as is the case for the compost + wood chips cover. However, results are more variable for both the compost only and green waste materials. For example, the organic solids varied between 20.5 and 38.1% in the two compost samples and between 31 and 45% for three green waste samples in 2006. In both cases, the samples from the shallowest cover (0.31m) had the lowest organic content suggesting that dilution with soil may be have an effect on the measured organic content. If this explanation were correct, then the cellulose + hemicellulose to lignin ratio (CH:L) would be consistent among all samples. While the CH:L is not perfectly consistent, it does exhibit less variability which suggests that soil may have resulted in some dilution in the 0.31 m covers. However, in the 2007 samples, the organic solids content was lowest in the thickest covers.

Table 14: Characterization of Biocovers<sup>a</sup>

	0.31 m Compost	0.91 m Compost	0.31 m Green waste	0.91 m Green waste
Solids (%)	69.1	60	53.5	35.4
Moisture (%)	30.9	40	46.5	64.6
Organic Content (% dry wt)	20.3	32.3	21.4	64.0
C:N	13.5	11.9	9.6	23
Carbon Loss/day (% of total C per day)	0.33	0.3	0.81	1.11
mg CO <sub>2</sub> -C/(g VS-day)	1.8	1.60	4.4	6.0
Total N	0.815	1.47	1.21	1.51
Total C	11.0	17.4	11.6	34.6

a. Tests were conducted by Woods End Research Laboratory in Mount Vernon, ME. Samples were collected in early February, 2006.

The composition of the solids in the various covers is summarized in Table 15. There was a consistent decrease in the moisture content of each cover between January, 2006 and April, 2007. This is consistent with the higher rainfall (2.37 in) and low evapotranspiration (1.4 in) in January, 2006 relative to low rainfall (1.61) and high evapotranspiration (5.14 in) in April, 2007 in Yolo County, CA. (<http://www.cimis.water.ca.gov/cimis/monthlyReport.do>).

Cellulose, hemicellulose and lignin represent the major biodegradable organics in vegetative matter. Over time, the cellulose and hemicellulose are expected to biodegrade more rapidly than the lignin. Thus, the cellulose plus hemicellulose to lignin ratio (CH/L) can be used as an indicator of biodegradation. The advantage of this ratio is that it eliminates any dilution with soil that would decrease the absolute concentrations of each compound.

The CH/L consistently decreased with time in the green waste but not in compost and compost + wood chips covers (Fig 9). The most dramatic decrease occurred in the thinnest cover (0.31 m) which may be due to the increased availability of oxygen in this cover. There was essentially no change in the CH/L of the compost covers which is consistent with the fact that the compost was the most decomposed material (lowest CH/L) initially. There was also a larger decrease in the CH/L in the 0.31 m compost + wood chips cover relative to the 0.91 m cover of the same materials. This too is consistent with the possibility that the additional availability of oxygen in the shallower cover enhanced biodegradation.

The organic solids content would also be expected to decrease over time but there is not a consistent trend (Fig. 9). The organic solids measure is less sensitive than the CH/L and would be affected by dilution with soil. The last column in Table 15, the fraction of the total organic solids that can be accounted for as cellulose, hemicellulose and lignin, is an internal check on the analyses. The range of values, 69.5 to 81.9% in 2006 and 61.4 to 82.4% in 2007 are typical of this type of analysis. The remaining organic matter includes small quantities of other compounds present in vegetative material.

It is also interesting that no cover material had an organic solid content above 44.6% in 2006 and 45.2% in 2007. This suggests that all materials, as applied to the landfill, contained significant quantities of soil. For purposes of comparison, the composition of fresh leaves, grass and branches, as measured in previous research, are also reported in Table 16. In all cases, the cellulose, hemicellulose and organic solids are considerably higher than the samples collected from the biocovers. This suggests that biodegradation has occurred in the biocover materials used, and that they have been diluted with soil.

In summary, there was measurable biodegradation of the green waste over a 15 month period. In practice, a thicker cover will mitigate this issue to some extent. It may be necessary to supplement green waste covers with fresh material at some interval. However, the field emissions data discussed next suggest that the 0.61 and 0.91 m green waste covers performed quite well. Additional monitoring of these covers would be desirable.

Table 15: Composition of Solids in the Test Covers in January-February, 2006 and April, 2007

Sample ID		H <sub>2</sub> O (%)	Cellulose (%)		Hemicellulose (%)		Lignin (%)		(Cell + Hemi) / Lignin	Organic solids (OS) (%)		(Cell+Hemi+Lig)/ OS <sup>a</sup>
			Avg.	RPD <sup>b</sup>	Avg.	RPD <sup>b</sup>	Avg.	RPD <sup>b</sup>		From avg.	Avg.	
0.91 m Compost (80%) + Wood Chips (20%)	2006	42.0	4.4	15.3	2.0	14.4	20.0	4.8	0.30	34.0	3.5	77.4
	2007	22.4	4.4	0.1	2.0	0.0	19.1	0.0	0.33	31.8	0.0	80.1
0.31 m Compost (80%) + Wood Chips (20%)	2006	43.4	4.8	1.0	2.1	2.7	19.1	0.4	0.40	32.0	5.1	81.4
	2007	20.3	4.4	0.0	1.8	0.0	20.3	0.0	0.30	35.7	0.0	74.2
0.31 m Compost	2006	30.7	1.4	9.0	0.8	11.2	12.1	4.0	0.20	20.5	1.4	69.5
	2007	20.6	3.5	0.1	1.8	0.1	21.7	0.0	0.24	37.0	0.0	73.2
0.91 m Compost	2006	44.7	4.1	16.4	1.8	10.3	25.0	6.2	0.20	38.1	0.6	81.3
	2007	22.9	2.5	0.0	1.4	0.0	19.2	0.0	0.20	32.5	0.0	70.8
0.91 m Green waste	2006	55.3	5.9	6.4	3.9	4.9	24.4	8.8	0.40	44.6	3.7	76.7
	2007	37.5	5.5	0.0	3.4	0.0	28.3	0.0	0.32	45.2	0.0	82.4
0.61 m Green waste	2006	54.8	3.6	2.0	2.8	2.3	22.3	9.9	0.30	35.1	0.6	81.9
	2007	22.9	3.4	0.0	2.6	0.0	23.2	0.0	0.26	43.4	0.0	67.3
0.31 m Green waste	2006	49.7	4.1	22.7	3.3	12.5	17.6	14.3	0.40	31.4	2.9	80.0
	2007 (a)	16.4	2.6	0.0	2.0	0.0	19.8	0.0	0.23	31.0	0.0	78.5
	2007 (b)	23.5	3.4	0.0	2.6	0.1	24.5	0.1	0.25	37.6	0.0	81.2
0.31 m Soil	2006	22.9	na		na		na		na	7.0	1.0	
	2007	13.3	0.1	0.1	0.1	0.0	3.1	0.1	0.07	6.1	0.0	54.4
0.31 m Green waste on side slopes	2007	18.4	3.4	0.0	2.5	0.0	23.1	0.0	0.25	36.9	0.0	78.4
0.31 m Green waste on side slopes	2007	11.9	0.4	0.0	0.4	0.0	5.0	0.0	0.17	9.6	0.1	61.4

- a. The fraction of the cellulose, hemicellulose and lignin that is accounted for in the organic solids analysis
- b. The relative percent deviation. This is the standard deviation of duplicate analyses divided by the mean

Table 16: Typical Solid Composition for Leaves and Grass Published in Literature

	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	(Cell + Hemi) / Lignin	Organic Solids (%)	(Cell+Hemi +Lig)/ OS
Leaves (Unpublished)	13.1	9	36.8	0.6		
Leaves (Eleazer et al., 1997)	15.3	10.5	43.8	0.6	90.2	77
Branches (Eleazer et al., 1997)	35.4	18.4	32.6	1.7	96.3	89
Grass (Eleazer et al., 1997)	26.5 & 25.6	10.2 & 14.8	28.4 & 21.6	1.3 & 1.9	85.0 & 87.8	77 & 71

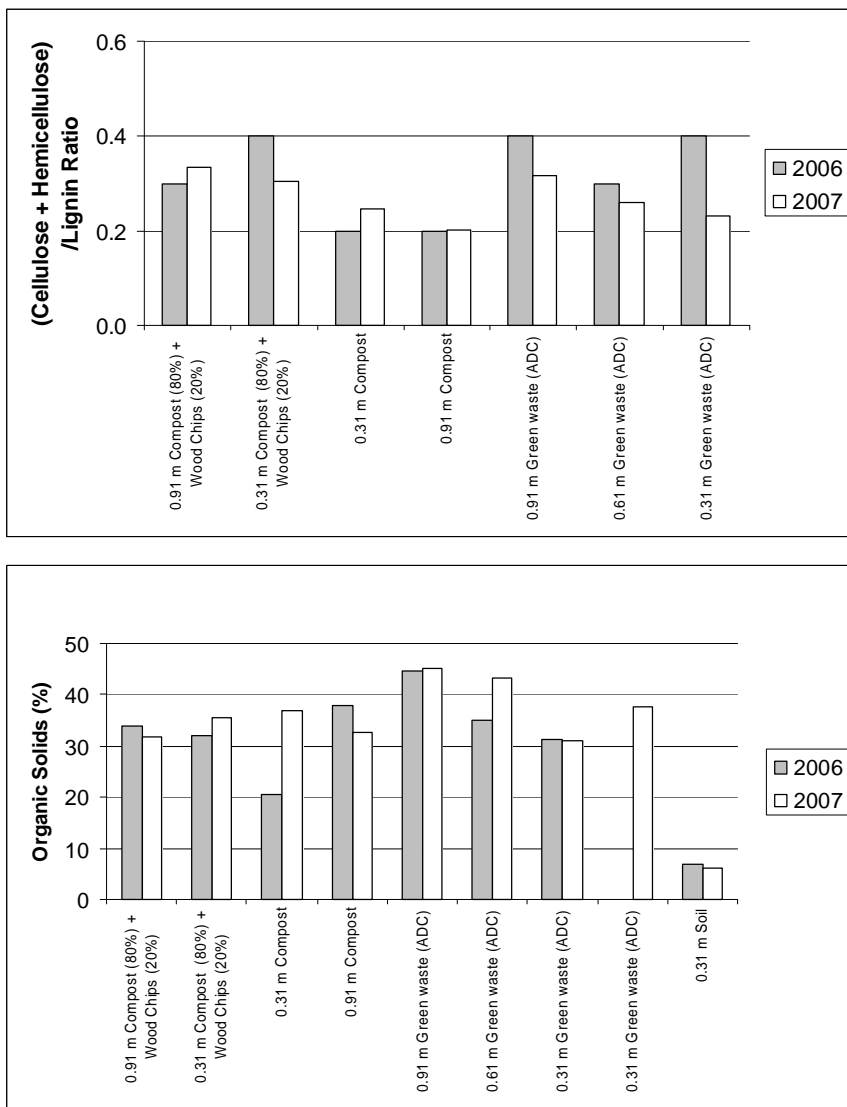


Figure 9: CH/L ratio and Organic Solids of different types of covers in 2006 and 2007

## Methane Emissions Tests

CH<sub>4</sub> emissions from the alternate covers during both the rainy season and dry season field tests are summarized in Table 17. Emissions were measured with the gas collection system at both a high setting, to simulate gas collection during peak power demand, and a low setting to simulate a time period when the objective was to store gas in the landfill.

In the rainy season tests, there was a statistically significant decrease in CH<sub>4</sub> emissions when the gas system vacuum was increased for the covers with the highest emissions (0.91 m compost + wood chips, 0.31 m compost, soil). The elevated emissions in the 0.91 m compost + wood chips, and in the 0.31 m compost are surprising as the compost was expected to promote the most CH<sub>4</sub> oxidation. All covers were noticeably wet, which could result in two factors that would promote CH<sub>4</sub> emissions. First, the moisture would fill up pore space that would otherwise be occupied by air. As the oxidation of CH<sub>4</sub> is dependent on the presence of O<sub>2</sub>, pore space filled with water would hinder CH<sub>4</sub> oxidation. In addition, the saturated nature of the cover materials could also promote anaerobic biodegradation and CH<sub>4</sub> production within the compost. To evaluate this possibility, a sample of each cover was put in a serum bottle on arrival at NC State University as a qualitative measure as to whether the samples were producing CH<sub>4</sub>. The only sample that did not produce CH<sub>4</sub> was the 0.91 m green waste. In fact, even the soil produced CH<sub>4</sub>. These results suggest that the wet nature of the biocovers precluded optimum CH<sub>4</sub> oxidation with the gas system in the low vacuum position.

In no case was there an increase in CH<sub>4</sub> emissions associated with reduced gas collection system vacuum during the dry season tests (Table 17). The seemingly high average flux for the soil cover is heavily influenced by one outlier (22.97 gm CH<sub>4</sub>/m<sup>2</sup>-day). This is also the case for the 0.31 m green waste cover which had the second highest average CH<sub>4</sub> emission. While limited, the data in Table 17 do not indicate increased emissions associated with the side slope. Individual flux measurements are presented in Tables 29 and 30.

CH<sub>4</sub> emissions during the rainy and dry seasons are also compared in Table 17. While the gas collection system was not operating at exactly the same level during the two different seasons, the comparison can provide some indication of the extent to which climate influences CH<sub>4</sub> oxidation at both high and low vacuum. At low vacuum, CH<sub>4</sub> emissions

were statistically higher during the rainy season in the 0.91 m compost + wood chips cover but not in the 0.31 m compost + wood chips cover. Similarly, CH<sub>4</sub> emissions were statistically higher in the 0.91 m compost cover but not in the 0.31 m compost cover. In the case of green waste, emissions were statistically higher during the rainy season at all thicknesses. Comparing CH<sub>4</sub> emissions between the rainy and dry seasons at high gas collection system vacuum, rainy season emissions were higher in the 0.31 m compost and 0.91 m green waste covers but lower in the 0.31 m green waste cover. In some cases biocover performed worse than soil cover. While there are many confounding issues, the data suggest that emissions at low vacuum during the rainy season are the highest.

Table 17: CH<sub>4</sub> Emissions for Alternate Covers During the Rainy and Dry Seasons (gm CH<sub>4</sub>/m<sup>2</sup>-day)

	Area	0.91 m compost + wood chips	0.31 m compost + wood chips	0.91 m compost	0.31 m compost	0.91 m green waste	0.61 m green waste	0.31 m green waste	0.31 m soil	0.31 m side slope green waste and shredded tires	0.31 m side slope close to bottom, green waste only
Rainy Season	<b>Gas System at Low Vacuum (47-63 cfm)</b>										
	<b>Average</b>	20.85 (a, b)	0.00	0.20 (b)	20.41 (a, b)	5.37 (b)	0.89 (b)	0.17 (b)	13.37 (a)	NM*	NM
	<b>Std. Dev.</b>	5.7	0.0	0.1	3.7	2.4	1.0	0.2	8.7	NM	NM
	<b>Gas System at High Vacuum (117 cfm)</b>										
	<b>Average</b>	3.28 (a)	0.00	0.14	2.28 (a,d)	3.34 (d)	0.21	0 (d)	1.68 (a)	NM	NM
<b>Std. Dev.</b>	3.20	0.00	0.12	1.43	2.06	0.35	0.00	0.55	NM	NM	
Dry Season	<b>Gas System at Low Vacuum (30 cfm)</b>										
	<b>Average</b>	0 (b)	0.005	0.0002 (b)	-0.003 (b)	0.015 (b)	0.002 (b)	1.998 (b)	5.255	NM	NM
	<b>Std. Dev.</b>	0	0.007	0.009	0.008	0.021	0.009	1.257	9.918	NM	NM
	<b>Gas System at High Vacuum (60 cfm)</b>										
	<b>Average</b>	0.002	-0.0004	0.000	-0.002(d)	0.021 (d)	0.002	1.65 (d)	1.123	-0.049	1.280
<b>Std. Dev.</b>	0.004	0.001	0.000	0.004	0.018	0.004	1.027	1.426	0.149	1.036	

\*NM = Not Measured

- Averages denoted with an “a” indicate a significant difference between the high and low vacuum tests during the rainy season (p<0.05).
- Averages denoted with a “b” indicate a significant difference between the rainy and dry season tests at low vacuum (p<0.05).
- Averages denoted with a “d” indicate a significant difference between the rainy and dry season tests at high vacuum (p<0.05).

Table 18: CH<sub>4</sub> Oxidation in Selected Samples During Rainy Season Tests (%)<sup>a</sup>

Area	0.91 m compost + wood chips	0.31 m compost + wood chips	0.91 m compost	0.31 m compost	0.91 m green waste	0.61 m green waste	0.31 m green waste	0.31 m soil
<b>Gas System at Low Vacuum (47-63 cfm)</b>								
1/23/2006	0		14.8	5.1	62.6			12.7
1/24/2006			13.2					
1/25/2006				6.7		74.5		
1/25/2006							0.5	16.9
1/25/2006	10.1				79.6		0.4	
<b>Gas System at High Vacuum (117 cfm)</b>								
1/30/2006	16					85.7		25.5
1/30/2006				8.8	98.1			23.5
1/31/2006	0		20.8					
1/31/2006				10.9	83.3			

a. For selected samples, the fraction of CH<sub>4</sub> passing through the cover that was oxidized was estimated from changes in the <sup>13</sup>C/<sup>12</sup>C ratio between landfill gas and emitted CH<sub>4</sub>. Data are presented as a % of CH<sub>4</sub> biologically oxidized while passing through a cover

Table 19: CH<sub>4</sub> Oxidation in Selected Samples During Dry Season Tests (%)<sup>a</sup>

Area	0.91 m compost + wood chips	0.31 m compost + wood chips	0.91 m compost	0.31 m compost	0.91 m green waste	0.61 m green waste	0.31 m green waste	0.31 m soil	Side Slope green waste and shredded tires	Side Slope close to bottom, green waste only
<b>Gas System at Low Vacuum (30 cfm)</b>										
11/15/2006							16.3	-4.2		
11/16/2006							16.5	-25.9		
11/16/2006							26	-20.9		
11/16/2006							12.6	-32.5		
11/16/2006							14.1	-15.3		
<b>Gas System at High Vacuum (60 cfm)</b>										
11/29/2006					4.93		22.9	-14.7		64.9
11/30/2006					12.1		24.2	-17.4		86.5
11/30/2006							25.6	-12		25.6
11/30/2006							15.9	-6		99.8

## Gas Profiles During Field Testing

Gas profile data of the alternate covers are summarized in Tables 20 and 21 for the rainy and dry season, respectively. Selected data are also presented in Figure 10. Similar to the emission tests, the profiles were measured with the gas collection system at both high and low vacuum. The clearest measure of the effect of climate is that CH<sub>4</sub> concentrations for the dry season were in the ppmv range while the corresponding concentrations were in the % range for the rainy season tests.

To evaluate the effect of the vacuum level, the CH<sub>4</sub> concentration closest to the surface was compared for each cover. During the rainy season, the elevated vacuum resulted in a decrease in the CH<sub>4</sub> concentration in the following covers: (1) 0.91 m compost + wood chips, (2) 0.31 m compost, (3) 0.61 m green waste and (4) 0.31 m soil. However, there was no effect in the 0.31 m compost + wood chips, and the 0.91 m compost, and the opposite trend was measured in the 0.91 and 0.61 m green waste. Thus, general statements on cover performance based on the CH<sub>4</sub> profile data are not possible. It seems likely that the high moisture levels in the covers dominated their performance. During the dry season tests, the CH<sub>4</sub> concentration closest to the surface was consistently lower during high vacuum. CH<sub>4</sub> concentrations were all below 150 ppmv, which is well below the 500 ppmv regulatory requirement at 15 cm above the cover.

In the 0.91 m compost + wood chips cover, the CH<sub>4</sub> concentration exhibited a maximum and the O<sub>2</sub> concentration a minimum at the middle depth during both the high and low vacuum samplings during the rainy season. The most logical explanation for this is that there was methane generation in microniches in this cover. However, there are not sufficient data to be conclusive.

The O<sub>2</sub> profile data for selected covers are illustrated in Fig. 10 although there are only limited data available. In the 0.91 m compost + wood chips, the 0.91 m compost and 0.91 m green waste, there appears to be a slight increase in O<sub>2</sub> at the deepest depth at high vacuum relative to low vacuum during the rainy season. This is consistent with the fact that there was less methane in the cover at high vacuum and also an increased gradient for O<sub>2</sub> infiltration. In addition, there was greater O<sub>2</sub> penetration in these covers during the dry season relative to the rainy season (Fig. 10) though there are insufficient data to assess the affect of vacuum during the dry season.

Table 20: Gas Composition Versus Cover Depth During The Rainy Season

Rainy Season							
Cover Type	Depth (cm)	Date	CH <sub>4</sub> (%)	CO <sub>2</sub> (%)	O <sub>2</sub> (%)	N <sub>2</sub> (%)	Gas Collection System Vacuum <sup>a</sup>
0.91 m compost + wood chips	15.2	1/23/06	21.0	19.6	11.7	47.8	Low
	35.6	1/23/06	43.6	43.5	1.6	11.3	
	53.3	1/23/06	36.4	38.1	5.1	20.4	
	15.2	1/26/06	3.6	6.1	21.6	68.8	High
	35.6	1/26/06	37.7	44.6	2.3	15.4	
	53.3	1/26/06	26.9	28.8	9.9	34.4	
	15.2	1/31/2006	2.3	5.1	22.3 <sup>b</sup>	70.2	High
	35.6	1/31/2006	28.8	41.4	2.0	27.8	
	53.3	1/31/2006	26.4	33.8	6.6	33.6	
0.31 m compost + wood chips	15.2	1/23/06	0.0	1.7	21.4	76.9	Low
	15.2	1/26/06	0.3	9.2	15.9	74.5	High
	15.2	1/31/06	0.0	9.5	13.2	77.5	High
0.91 m compost	15.2	1/23/06	0.43	0.30	24.5 <sup>b</sup>	74.8	Low
	34.3	1/23/06	28.5	22.5	2.5	46.4	
	59.7	1/23/06	36.0	19.5	3.1	41.4	
	15.2	1/26/06	0.0	0.3	24.7 <sup>b</sup>	75.0	High
	34.3	1/26/06	32.0	24.4	3.5	40.1	
	59.7	1/26/06	40.8	23.5	2.2	33.5	
	15.2	1/31/2006	0.3	0.3	26.5 <sup>b</sup>	73.0	High
	34.3	1/31/2006	27.6	26.5	2.9	43.0	
	59.7	1/31/2006	26.5	20.7	7.5	45.1	
0.91 m green waste	15.2	1/23/06	0.4	14.5	12.0	73.0	Low
	30.5	1/23/06	5.6	28.7	2.9	62.7	
	15.2	1/26/06	0.7	6.3	19.8	73.2	High
	30.5	1/26/06	12.2	29.7	5.0	53.1	
	15.2	1/31/2006	12.2	27.5	4.2	56.1	High
	30.5	1/31/2006	1.3	12.3	14.8	71.5	

a. Low vacuum: 47-63 cfm and high vacuum: 117 cfm

Table 20: Gas Composition Versus Cover Depth During The Rainy Season (Continued)

Rainy Season							
Cover Type	Depth (cm)	Date	CH <sub>4</sub> (%)	CO <sub>2</sub> (%)	O <sub>2</sub> (%)	N <sub>2</sub> (%)	Gas Collection System Vacuum <sup>a</sup>
0.31 m compost	15.2	1/23/06	23.4	24.6	12.2	39.7	Low
	15.2	1/26/06	5.6	5.6	21.6	67.2	High
	15.2	1/31/2006	4.2	6.0	22.6 <sup>b</sup>	67.1	High
0.31 m green waste	15.2	1/23/06	0.2	1.4	22.7 <sup>b</sup>	75.8	Low
	15.2	1/26/06	0.0	1.6	25.1 <sup>b</sup>	73.3	High
	15.2	1/31/2006	0.0	2.2	23.8 <sup>b</sup>	74.2	High
0.31 m green waste	15.2	1/26/06	0.4	0.7	25.8 <sup>b</sup>	72.9	High
	15.2	1/31/2006	14.0	12.5	13.6	57.7	High
0.61 m green waste	15.2	1/23/06	17.5	16.1	7.5	58.9	Low
	15.2	1/26/06	3.6	7.0	18.2	71.2	High
	15.2	1/31/2006	5.7	15.3	10.8	68.1	High
0.31 m soil	15.2	1/23/06	6.6	3.4	21.9 <sup>b</sup>	68.0	Low
	15.2	1/26/06	0.3	0.0	26.7 <sup>b</sup>	73.0	High
	15.2	1/31/2006	0.2	0.0	26.7 <sup>b</sup>	73.1	High

a. Low vacuum: 47-63 cfm and high vacuum: 117 cfm

b. O<sub>2</sub> concentrations greater than 21% reflect analytical error.

Table 21: Gas Composition Versus Cover Depth During The Dry Season

Dry Season							
Cover Type	Depth (cm)	Date	CH <sub>4</sub> (ppm)	CO <sub>2</sub> (%)	O <sub>2</sub> (%)	N <sub>2</sub> (%)	Gas Collection System Vacuum <sup>a</sup>
0.91 m compost + wood chips	17.8	11/15/2006	19	4.5	17.0	78.5	Low
	33.0	11/15/2006	12	4.2	17.2	78.6	
	50.8	11/15/2006	14	7.8	13.3	78.9	
	17.8	11/30/2006	11	2.5	18.6	78.9	High
	33.0	11/30/2006	8	2.8	18.2	79.0	
	50.8	11/30/2006	73	4.4	16.4	79.2	
0.31 m compost + wood chips	16.5	11/15/2006	34	4.6	17.0	78.3	Low
	16.5	11/30/2006	13	1.8	19.8	78.4	High
0.91 m compost	17.8	11/15/2006	22	7.0	14.6	78.4	Low
	31.8	11/15/2006	26	9.3	11.3	79.4	
	57.2	11/15/2006	138	13.2	6.6	80.2	
	17.8	11/30/2006	8	4.0	17.2	78.8	High
	31.8	11/30/2006	11	6.9	13.7	79.4	
	57.2	11/30/2006	73	12.0	7.8	80.1	
0.91 m green waste	25.4	11/15/2006	55	4.7	16.3	79.0	Low
	30.5	11/15/2006	40	4.6	16.8	78.6	
	0.0						
	17.8	11/30/2006	31	4.7	16.3	79.0	High
	25.4	11/30/2006	11	4.7	15.9	79.3	
0.31 m compost	20.3	11/15/2006	8	1.8	20.2	78.0	Low
	20.3	11/30/2006	18	0.0	21.0	79.0	High
0.31 m green waste	17.8	11/15/2006	90	3.0	18.4	78.6	Low
	17.8	11/30/2006	54	2.0	19.3	78.6	High

a. Low vacuum: 30 cfm and high vacuum: 60 cfm

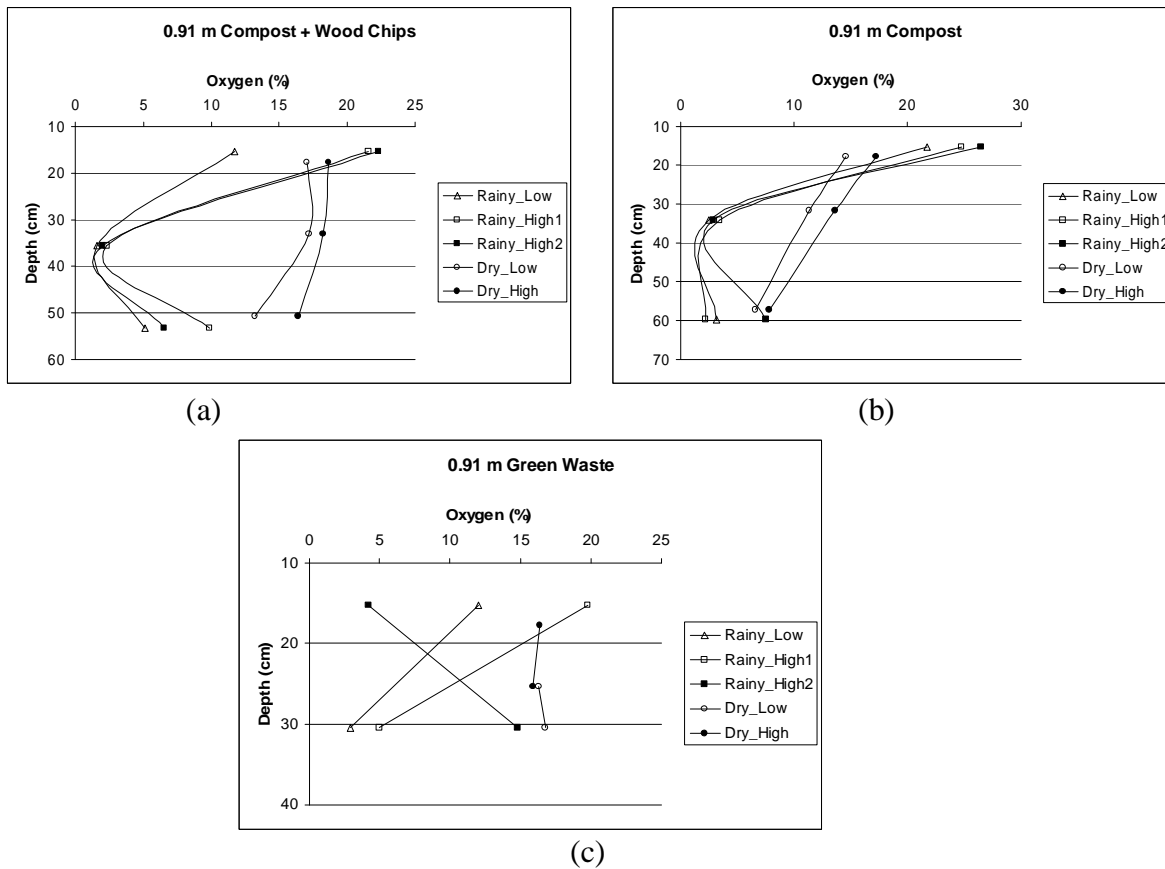


Figure 10: O<sub>2</sub> profiles in a. 0.91 m compost + wood chips, b. 0.91 m compost and c. 0.91 m green waste

### Discussion of Field Methane Emissions Data

The measured methane fluxes, selected profile data and methane oxidation data are summarized in Tables 22 and 23. In general, there is consistency between these three measures. During the rainy season at low vacuum, the covers with the highest measured fluxes were the 0.91 m compost + wood chips, the 0.31 m compost and the soil. These three covers had the most CH<sub>4</sub> at the top of the cover and among the lowest methane oxidation fractions. This latter measure must be used with some caution for several reasons. First, methane oxidation was not measured on every sample. Second, methane oxidation is only measured in samples with a positive flux. Third, 20% oxidation in a cover with a flux of 100 CH<sub>4</sub>/(m<sup>2</sup>-day) is more significant than 50% oxidation in a cover with a flux of 10 gm CH<sub>4</sub>/(m<sup>2</sup>-day). Fluxes at high vacuum were sufficiently low that a relationship between methane flux, profile and methane oxidation is less clear. However, even here two of the three covers with the highest fluxes (0.91 m compost + wood chips, 0.31 m compost) have the highest methane at the top of the cover and the lowest % methane oxidation. During the

dry season, fluxes were so low and profile data sufficiently sparse that no discussion of relationships between flux, profiles and methane oxidation is warranted.

Table 22: CH<sub>4</sub> Flux, CH<sub>4</sub> and O<sub>2</sub> Cover Concentration and CH<sub>4</sub> Oxidation During The Rainy Season

Low Vacuum (47-63 cfm)					
Cover Type	Depth (m)	CH <sub>4</sub> Flux (gm/m <sup>2</sup> -d)	CH <sub>4</sub> Concentration <sup>a</sup> (%)	O <sub>2</sub> Concentration <sup>a</sup> (%)	Oxidation <sup>b</sup> (%)
compost + wood chips	0.91	20.85 ± 5.7	21, 43.6, 36.4	11.7, 1.6, 5.1	0, 10.1
compost + wood chips	0.31	0.0	0.0	21.4	
compost	0.91	0.2 ± 0.1	0.12, 28.5, 36	23.1, 2.5, 3.1	14.8, 13.2
compost	0.31	20.41 ± 3.7	23.4	12.2	5.1, 6.7
green waste	0.91	5.37 ± 2.4	0.4, 5.6	12.0, 2.9	62.6, 79.6
green waste	0.61	0.89 ± 1.0	17.5	7.5	74.5
green waste	0.31	0.17 ± 0.2	0.2	22.7	0.5, 0.4
soil	0.31	13.37 ± 8.7	6.6	21.9	12.7, 16.9
High vacuum (117 cfm)					
compost + wood chips	0.91	3.28 ± 3.2	i. 3.6, 37.7, 26.9 ii. 2.3, 28.8, 26.4	i. 21.6, 2.3, 9.9 ii. 22.3, 2.0, 6.6	16, 0
compost + wood chips	0.31	0.0	i. 0.3 ii. 0.0	i. 15.9, 13.2	
compost	0.91	0.14 ± 0.12	i. 0.0, 32.0, 40.8 ii. 0.3, 27.6, 26.5	i. 24.7, 3.5, 2.2 ii. 26.5, 2.9, 7.5	20.8
compost	0.31	2.28 ± 1.43	i. 5.6 ii. 4.2	i. 21.6 ii. 22.6	8.8, 10.9
green waste	0.91	3.34 ± 2.06	i. 0.7, 12.2 ii. 12.2, 1.3	i. 19.8, 5.0 ii. 4.2, 14.8	98.1, 83.3
green waste	0.61	0.21 ± 0.35	i. 3.6 ii. 5.7	i. 18.2 ii. 10.8	85.70
green waste	0.31	0.0	i. 0.0 ii. 0.4 iii. 14.0	i. 24.45 ii. 25.8, iii. 13.6	
soil	0.31	1.68 ± 0.55	i. 0.3 ii. 0.2	i. 26.7 ii. 26.7	25.5, 23.5

- a. CH<sub>4</sub>, O<sub>2</sub>, CO<sub>2</sub> and N<sub>2</sub> concentrations at specific depths are documented in Table 20. The CH<sub>4</sub> and O<sub>2</sub> concentrations measured in shallow (15.2 cm), medium (30.5-35.6 cm) and deep (53.3-59.7 cm) depth of each cover are entered in order in each cell. A single entry represents the shallowest depth and a double entry represents shallow and medium depth where applicable. The notation (i), (ii) and (iii) in single cell represents multiple samplings.
- b. For selected samples, the fraction of CH<sub>4</sub> passing through the cover that was oxidized was estimated from changes in the <sup>13</sup>C/<sup>12</sup>C ratio between landfill gas and emitted CH<sub>4</sub>. Data are presented as a % of methane biologically oxidized while passing through a cover. % CH<sub>4</sub> oxidation was only calculated in static chambers for which there was a positive emission.

Table 23: CH<sub>4</sub> Flux, CH<sub>4</sub> and O<sub>2</sub> Cover Concentration and CH<sub>4</sub> Oxidation During The Dry Season

Low Vacuum (30 cfm)					
Cover Type	Depth (m)	CH <sub>4</sub> Flux (gm/m <sup>2</sup> -d)	CH <sub>4</sub> Concentration <sup>a</sup> (ppm)	O <sub>2</sub> Concentration <sup>a</sup> (%)	Oxidation <sup>b</sup> (%)
compost + wood chips	0.91	0.0	19, 12, 14	17, 17.2, 13.3	
compost + wood chips	0.31	0.005 ± 0.007	34	17	
compost	0.91	0.0002 ± 0.009	22, 26, 138	14.6, 11.3, 6.6	
compost	0.31	-0.003 ± 0.008	8	20.2	
green waste	0.91	0.015 ± 0.021	NR, 55, 30.5	NR, 16.3, 16.8	16.3, 16.5, 26, 12.6, 14.1
green waste	0.61	0.002 ± 0.009			
green waste	0.31	1.998 ± 1.257	90	18.4	
soil	0.31	5.255 ± 9.918			
High Vacuum(60 cfm)					
compost + wood chips	0.91	0.002 ±	11, 8, 73	18.6, 18.2, 16.4	
compost + wood chips	0.31	-0.0004 ± 0.001	13	19.8	
compost	0.91	0	8, 11, 73	17.2, 13.7, 7.8	
compost	0.31	-0.002 ± 0.004	18.0	21.0	
green waste	0.91	0.021 ± 0.018	31, 11	16.3, 15.9	4.93, 12.1
green waste	0.61	0.002 ± 0.004			
green waste	0.31	1.65 ± 1.027	54	19.3	22.9, 24.2, 25.6, 15.9
soil	0.31	1.123 ± 1.426			-14.7, -17.4, -12, -6
green waste + shredded tires		-0.049 ± 0.149			
green waste		1.28 ± 1.036			64.9, 86.5, 25.6, 99.8

- a. CH<sub>4</sub>, O<sub>2</sub>, CO<sub>2</sub> and N<sub>2</sub> concentrations at specific depths are documented in Tables 21. The CH<sub>4</sub> and O<sub>2</sub> concentrations measured in shallow (15.2 cm), medium (30.5-35.6 cm) and deep (53.3-59.7 cm) depth of each cover are entered in order in each cell. A single entry represents the shallowest depth and a double entry represents shallow and medium depth where applicable. The notation (i), (ii) and (iii) in single cell represents multiple samplings.
- b. For selected samples, the fraction of CH<sub>4</sub> passing through the cover that was oxidized was estimated from changes in the <sup>13</sup>C/<sup>12</sup>C ratio between landfill gas and emitted CH<sub>4</sub>. Data are presented as a % of methane biologically oxidized while passing through a cover. % CH<sub>4</sub> oxidation was only calculated in static chambers for which there was a positive emission.

## Discussion

The column experiments were conducted to evaluate the performance of a biologically active cover material and the effects of pressure gradient, moisture infiltration and CH<sub>4</sub> flow regime on CH<sub>4</sub> oxidation. The initial flux of 5 mL/min or 294.4 gm CH<sub>4</sub>/m<sup>2</sup>-d is in the midrange of reported landfill CH<sub>4</sub> fluxes (Kunz and Lu, 1980; Jones and Nedwell, 1990, 1993; Bogner and Spokas, 1993). The higher flux rates of 588.6 and 883.01 gm CH<sub>4</sub>/m<sup>2</sup>-d later were at the upper range of reported values although fluxes above 1000 have been reported (Abichou et al., 2006b). As summarized in Figures 5 to 6 and Table 9, methane oxidation decreased as the flux or pressure gradient increased. The CH<sub>4</sub> flux exceeded the oxidation capacity of the system, presumably because there was insufficient retention time in regions where CH<sub>4</sub> and O<sub>2</sub> mixed. This observation is reinforced in the columns that did not receive a water addition by the considerable increase in CH<sub>4</sub> oxidation when the CH<sub>4</sub> feeding rate was decreased from 883.01 to 147.2 gm/m<sup>2</sup>-day. This result is consistent with the decrease in CH<sub>4</sub> oxidation with increasing flow in the range of 160 to 319 gm CH<sub>4</sub>/m<sup>2</sup>-d reported previously (Stein and Hettiaratchi, 2000).

The addition of moisture was inhibitory for O<sub>2</sub> diffusion in the compost as evidenced by the reduced O<sub>2</sub> concentrations at depth in the water addition columns (Table 11, 12 and Fig. 7). This is consistent with the observation of standing water in the columns when they were destructively sampled. The excess moisture hindered oxygen diffusion which is required for CH<sub>4</sub> oxidation. The inhibitory effect of water addition on methane oxidation was most apparent at the end of the experiment at the 147.2 gm/m<sup>2</sup>-day flux. The inhibitory effect would be expected to increase over time as moisture was added weekly. Thus, it is logical that the effect was clearest near the end of the experimental work.

The highest oxidation rate reported previously, 410.1 gm CH<sub>4</sub>/m<sup>2</sup>-d, represents 100% oxidation in columns filled with municipal solid waste compost (Humer and Lechner, 1999). Other laboratory-scale CH<sub>4</sub> oxidation rates include 166 gm CH<sub>4</sub>/m<sup>2</sup>-d (Kightley et al., 1995), 100 gm CH<sub>4</sub>/m<sup>2</sup>-d (Visvanathan et al., 1999), and 144 gm CH<sub>4</sub>/m<sup>2</sup>-d (Stein and Hettiaratchi, 2000). The maximum oxidation rate measured in this study was 664.2 gm CH<sub>4</sub>/m<sup>2</sup>-d observed in Column 2. The average CH<sub>4</sub> oxidation rates observed in this study are comparable with reported oxidation rates for biocovers and higher than oxidation rates

reported for soil covers (Humer and Lechner, 1999; Berger et al., 2005; Hilger et al., 2000; Kightley et al., 1995; Visvanathan et al., 1999; Stein and Hettiaratchi, 2000).

Field-scale experiments were conducted to assess the performance of several different cover materials under varying climatic conditions and LFG collection vacuum. The effect of climate was significant. In the rainy season tests, there was a statistically significant decrease in CH<sub>4</sub> emissions when the gas system vacuum was increased for the covers with the highest emissions (0.91 m compost + wood chips, 0.31 m compost, soil). In contrast, there was not an increase in CH<sub>4</sub> emissions associated with reduced gas collection system vacuum during the dry season tests (Table 17). While there were many confounding issues, the data suggest that emissions at low vacuum during the rainy season are the highest (Tables 17) but that overall, the covers were effective in controlling gas release. The emissions data are consistent with the gas profile data where CH<sub>4</sub> concentrations for the dry season were in the ppmv range while the corresponding concentrations were in the % range for the rainy season tests.

In the field, the highest CH<sub>4</sub> emission was 20.85 gm CH<sub>4</sub>/m<sup>2</sup>-d in 0.91 m compost + wood chips and 5.255 gm CH<sub>4</sub>/m<sup>2</sup>-d in 0.31 m soil during the rainy and dry season, respectively. When CH<sub>4</sub> oxidation was measured, it varied from 5 to over 99% in the field. These values are consistent with the previously reported field scale studies though some extreme values are also available (Abichou et al., 2006a; Abichou et al., 2006b; Borjesson et al., 2001; Abichou et al., 2005; Barlaz et al., 2004; Schuetz et al., 2003; Humer and Lechner, 2001; Borjesson et al., 2001; Borjesson et al., 1993; Jones and Nedwell, 1993). Emissions of 9 to 130 gm CH<sub>4</sub>/m<sup>2</sup>-d have been reported at landfill sites in the northeastern United States (Chanton et al., 1999). The highest reported field-scale CH<sub>4</sub> oxidation rates are 214.4 gm CH<sub>4</sub>/m<sup>2</sup>-d (Humer and Lechner, 2001) and 149.8 gm CH<sub>4</sub>/m<sup>2</sup>-d (Borjesson et al., 1997) although these values may be an underestimate since methane oxidation could only be measured when it was positive.

Both the field and lab results indicate that high moisture can inhibit methane oxidation. As the overall objective of this project was to assess the efficacy of the peak power concept, it is encouraging to note that during the dry season, there was no increase in emissions during periods when the gas collection system vacuum was reduced.

There was an increase in CH<sub>4</sub> emissions at low vacuum during the rainy season. However, this may not be critical as the hottest temperatures and associated highest demand for electricity are likely to occur during the dry season. The results suggest that it would be prudent to operate the gas system to maximize methane collection during periods when then cover soils are saturated with moisture as during this state, CH<sub>4</sub> oxidation will likely be reduced. Further field tests would be required to more precisely determine the extent to which slight reductions in gas collection vacuum may be possible when the cover is saturated. Except the soil and 0.31 m green waste, all covers of different thicknesses performed well. So the cover type to be used in the field should be based on availability of the material and cost.

### **Recommendations for Further Research**

The following experiments should be addressed to characterize the performance of biocover in variable environmental conditions-

1. Composition of biocover needs to be optimized to balance porosity and infiltration capacity with the potential for emissions associated with cracks.
2. Excess rainfall can reduce the O<sub>2</sub> diffusion in biocover. Optimization of sufficient moisture for bacteria growth based on biocover types should be documented.
3. In laboratory column experiments, evidence of decreasing methane oxidation capacity was observed at higher pressure gradients. Further research should be performed to characterize this effect through modeling. The effects of gas flow rate, compost moisture content, column diameter and depth (i.e. retention time), and compost porosity should be addressed in the modeling to identify an optimal system.
4. Cover moisture contents should be monitored to document how much infiltration is tolerable before a decrease in oxidation is observed.
5. The O<sub>2</sub> demand of cover materials should be tested before use. The compost must be a matured substrate with reported respiratory activity in 7 days at less than 10 mg O<sub>2</sub>.g<sup>-1</sup> DM. Field and laboratory scale research should be performed to justify the applicability of this value in CH<sub>4</sub> oxidation.

6. The durability and active life of cover material should be studied over long time periods. This can be addressed by documenting the amount of solid decomposition in the field and trends in CH<sub>4</sub> oxidation over time.

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## **Appendix**

Appendix 1  
**Stable Carbon Isotope Analysis<sup>2</sup>**

The technique for the in-situ determination of CH<sub>4</sub> oxidation is based upon measuring the difference in δ<sup>13</sup>C between produced or anoxic zone CH<sub>4</sub>, which is not affected by oxidation, and that emitted from the landfill cover soil that has been subjected to oxidation (Chanton et al., 1999). Combined with estimates of the preference of the bacteria for <sup>12</sup>CH<sub>4</sub> relative to <sup>13</sup>CH<sub>4</sub>, α, the fraction of CH<sub>4</sub> oxidized as it passes through a landfill cover soil can be estimated.

For chamber incubations in which the CH<sub>4</sub> concentration increased over time, the fraction oxidized was determined by equation 1 (Chanton et al., 1999), which describes isotopic fractionation in an open system:

$$f_o = [(\delta E - \delta A) / (\alpha_{ox} - \alpha_{trans})] * 1000 * 100 \quad (1)$$

where,  $f_o$  is the % of CH<sub>4</sub> oxidized in transit through the cover,  $\delta E = \delta^{13}C$  value of emitted CH<sub>4</sub>,  $\delta A = \delta^{13}C$  value of anoxic zone CH<sub>4</sub>,  $\alpha_{ox}$  is the isotopic fractionation factor for bacterial oxidation and  $\alpha_{trans}$  is the isotopic fractionation factor associated with gas transport. Some have argued that gas transport across the cover is dominated by advection (Liptay et al., 1998; Bergamaschi et al., 1998). Therefore,  $\alpha_{trans}$  was assumed to be 1. If diffusion is important in CH<sub>4</sub> transport, then  $\alpha_{trans}$  will be >1, and equation 1 defines the lower limit of CH<sub>4</sub> oxidation (De Visscher et al., submitted). The term α is defined as  $k_l/k_h$  where  $k_l$  and  $k_h$  refer to the rate constants of the light and heavy isotope, respectively. The bacterial fractionation factor associated with methanotrophic metabolism was determined from incubations of landfill cover samples at different temperatures (Chanton and Liptay, 2000).

Anoxic zone CH<sub>4</sub> (δA) was collected from the gas collection header. Gas collected from a header is representative of anoxic zone CH<sub>4</sub> as there is very little spatial and almost no temporal variability in the isotopic composition of landfill CH<sub>4</sub> (Chanton and Liptay, 2000; Chanton et al., 1999). Emitted CH<sub>4</sub> was collected from the headspace of the static chambers. The measured CH<sub>4</sub> δ<sup>13</sup>C at the end of a chamber test was corrected for the

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<sup>2</sup> This section was written by Dr. Jeff Chanton at Florida State University in support of the overall project and is included in this thesis to document all results.

presence of initial CH<sub>4</sub> through a mass balance to obtain the δ<sup>13</sup>C of accumulated CH<sub>4</sub> ([CH<sub>4</sub>]<sub>xs</sub>). This term defines the δ<sup>13</sup>C of CH<sub>4</sub> added to (or removed from) the CH<sub>4</sub> in the chamber at the start of the flux measurement (eqn. 2):

$$[\delta\text{CH}_4]_{\text{xs}} = (([\text{CH}_4]_{(\text{meas})} * [\delta\text{CH}_4]_{(\text{meas})}) - ([\text{CH}_4]_{\text{i}} * [\delta\text{CH}_4]_{\text{i}})) / ([\text{CH}_4]_{(\text{meas})} - [\text{CH}_4]_{\text{i}}) \quad (2)$$

Where, [CH<sub>4</sub>]<sub>(meas)</sub> and [δCH<sub>4</sub>]<sub>(meas)</sub> represent the concentration and δ<sup>13</sup>C value of CH<sub>4</sub> in the chamber at the final time, [CH<sub>4</sub>]<sub>i</sub> and [δCH<sub>4</sub>]<sub>i</sub> represent the concentration and δ<sup>13</sup>C value of chamber CH<sub>4</sub> at the initiation of the experiment, and [CH<sub>4</sub>]<sub>xs</sub> and [δCH<sub>4</sub>]<sub>xs</sub> represent the “excess” CH<sub>4</sub> or CH<sub>4</sub> added (or removed) from the chamber over the incubation time and its isotopic value.

### **Quantification of Methane Oxidation by Stable Isotope Analysis**

Selected samples were analyzed to quantify the % oxidation in the covers by using the stable isotope method. Rainy season CH<sub>4</sub> oxidation results are summarized in Table 18. It is important to note that a % CH<sub>4</sub> oxidation can only be calculated in static chambers for which there was a positive emission. Thus, the absence of CH<sub>4</sub> oxidation in the 0.31 m compost + wood chips cover should not be considered as a poorly performing cover as the average CH<sub>4</sub> flux was zero (Table 17). With the exception of the 0.91 m and 0.61 m green waste cover, CH<sub>4</sub> oxidation was relatively low. The most likely explanation for this is that the covers were so wet as to limit CH<sub>4</sub> oxidation. The high CH<sub>4</sub> oxidation in the 0.91 m green waste cover is interesting as this cover also had the highest emission level during the rainy season. This suggests that relatively high amounts of CH<sub>4</sub> passed through this cover and that some was oxidized. As noted above, despite the wet nature of the cover, there was no indication that the cover was producing CH<sub>4</sub>.

Dry season CH<sub>4</sub> oxidation data are presented in Table 19. When observed, CH<sub>4</sub> oxidation varied from 5 to over 99%. The large number of measurements exhibiting negative values is quite unusual. In every case, these anomalous values were associated with the one foot soil cover. It may be that the gas extraction system was particularly effective during this test in this particular area and caused air flow downward into the soil. In systems where CH<sub>4</sub> diffuses upwards against a flow of downward air, negative isotopic values of emitted CH<sub>4</sub>

have been observed. However, there were an equal number of observations of negative values at both low and high vacuum which is somewhat surprising. More negative values under high flow would have been expected if this explanation is correct.

## Appendix 2

### Tracer Test

A tracer test was performed to measure the water saturation in the compost and also to obtain information about the pore structure of compost inside the column. The test was conducted in columns 1 and 2 to look for evidence of short-circuiting that might affect the reproducibility of results. Column 1 and 2 did not receive any water during the methane oxidation test period.

About 100 mL of a gas mixture (99% helium and 1% difluoromethane [DFM]) was injected from the bottom of the columns at a flow rate of 24 mL/min for about 4 min. The tracer gas was injected by a syringe pump with a 100 mL syringe. The syringe was connected to a tygon tube and the tube was connected to T-connection which was again connected to the bottom of the column through tygon tube. The gas flow (50% CH<sub>4</sub> / 50% CO<sub>2</sub>) was fed to the columns through the other part of the T-connection at a flow rate of 15 mL/min. The air flow rate was increased to 85 mL/min during the test to facilitate tracer recovery. The gas was collected from the top of the columns at 15 minutes intervals. The breakthrough curves for columns 1 and 2 are presented below. The breakthrough curves of He and DFM for column 1 suggest reasonably uniform flow. The results for column 2 suggest less uniform flow than in column 1. Unfortunately, much of the column 2 data are scattered and with some points below the GC detection limit of 500 and 5 ppm for He and DFM, respectively. In case of He, the peak in column 1 occurred at 100 min while there was no defined peak in column 2. The limited results suggest that the flow behavior in columns 1 and 2 was different.

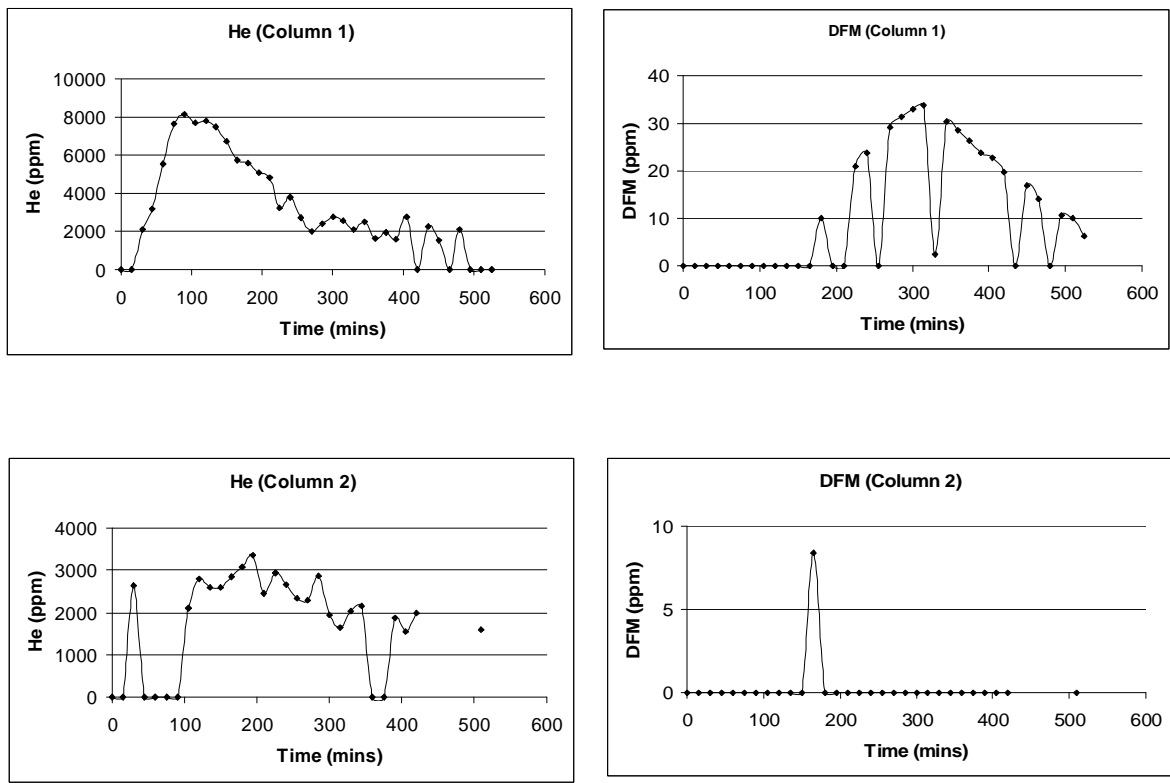


Figure 11: Tracer Test Breakthrough Curves

Appendix 3

Table 24: Gas Composition Profiles at Different Depths of the Columns on the 4<sup>th</sup> Day of the Experiment at a Gas Flow Rate of 5 mL/min and Air Flow Rate of 50 mL/min

Column *	Depth Below Top of the Compost (cm)	CO <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CH <sub>4</sub>
1	5.1	22.0	10.7	50.7	16.6
	20.3	44.5	1.4	8.6	45.4
	35.6	43.2	2.2	8.3	46.3
	50.8	45.6	1.1	3.7	49.6
2	5.1	11.7	12.6	70.0	5.7
	20.3	34.8	2.7	30.2	32.4
	35.6	43.0	1.2	9.1	46.6
	50.8	44.0	1.3	6.7	48.0
3	5.1	20.9	11.8	50.6	16.6
	20.3	42.1	1.9	16.8	39.2
	35.6	43.8	1.6	9.9	44.7
	50.8	45.3	1.1	4.9	48.7
5	5.1	22.6	11.4	47.5	18.6
	20.3	41.4	2.4	17.3	38.9
	35.6	44.5	1.4	7.9	46.2
	50.8	45.0	1.2	4.9	48.8
7	5.1	33.6	6.2	31.0	29.3
	20.3	44.6	1.5	5.3	48.6
	35.6	44.3	1.6	5.2	48.8
	50.8	45.7	1.1	3.0	50.3
8	5.1	16.5	11.5	61.5	10.5
	20.3	33.9	4.0	32.6	29.5
	35.6	43.0	1.2	11.7	44.1
	50.8	43.2	1.5	8.9	46.3

\*No column 6 data due to problems with mass flow controller

Table 25: Gas Composition Profiles at Different Depths of the Columns on the 55<sup>th</sup> Day of the Experiment at a Gas Flow Rate of 5 mL/min and Air Flow Rate of 50 mL/min

Column	Depth Below Top of the Compost (cm)	CO <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CH <sub>4</sub>
1	5.1	41.5	6.1	37.0	15.3
	20.3	46.8	1.5	5.0	46.7
	35.6	44.8	1.8	7.3	46.1
	50.8	46.9	0.9	3.3	48.9
2	5.1	17.1	11.2	64.5	7.3
	20.3	0.3	21.5	77.9	0.3
	35.6	47.4	0.7	3.0	49.0
	50.8	46.7	0.8	3.0	49.5
3	5.1	47.6	0.6	1.7	50.2
	20.3	47.1	0.6	1.8	50.4
	35.6	47.7	0.7	2.0	49.6
	50.8	47.4	0.7	2.0	49.9
5	5.1	27.9	6.2	49.6	16.2
	20.3	39.8	2.7	23.2	34.2
	35.6	46.8	0.6	6.7	45.9
	50.8	47.3	0.6	3.5	48.6
6	5.1	19.3	9.1	63.3	8.3
	20.3	28.2	7.0	44.6	20.2
	35.6	38.9	3.5	22.4	35.2
	50.8	36.1	5.4	23.3	35.2
7	5.1	47.1	0.7	1.9	50.4
	20.3	47.5	0.7	1.9	49.9
	35.6	47.7	0.6	1.6	50.2
	50.8	47.9	0.6	1.6	49.9
8	5.1	46.9	0.7	2.1	50.3
	20.3	47.6	0.6	1.6	50.2
	35.6	46.7	0.9	2.7	49.7
	50.8	47.5	0.6	1.5	50.4

Table 26: Gas Composition Profiles at Different Depths of the Columns on the 62<sup>nd</sup> Day of the Experiment at a Gas Flow Rate of 10 mL/min and Air Flow Rate of 50 mL/min

Column	Depth Below Top of the Compost (cm)	CO <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CH <sub>4</sub>
1	5.1	35.9	5.3	32.0	26.8
	20.3	46.7	1.5	5.0	46.8
	35.6	44.5	2.4	8.4	44.6
	50.8	47.9	0.9	2.4	48.8
2	5.1	27.7	8.8	44.5	19.0
	20.3	NA	NA	NA	NA
	35.6	48.4	0.8	2.1	48.7
	50.8	47.9	0.9	2.5	48.7
3	5.1	49.0	0.6	1.7	48.6
	20.3	48.9	0.6	1.5	49.0
	35.6	48.6	0.7	1.7	49.0
	50.8	48.0	0.8	2.1	49.1
5	5.1	40.1	3.3	26.5	30.1
	20.3	47.0	1.3	6.4	45.3
	35.6	48.2	0.8	2.6	48.4
	50.8	48.4	0.7	1.7	49.2
6	5.1	32.0	5.5	41.0	21.5
	20.3	38.4	4.6	21.7	35.3
	35.6	46.5	1.5	5.9	46.1
	50.8	NA	NA	NA	NA
7	5.1	48.6	0.8	2.2	48.4
	20.3	48.6	0.8	1.9	48.8
	35.6	48.2	0.9	2.2	48.7
	50.8	48.2	0.8	1.8	49.2
8	5.1	48.8	0.7	1.9	48.6
	20.3	48.6	0.7	1.6	49.1
	35.6	NA	NA	NA	NA
	50.8	48.2	0.7	1.7	49.3

NA = Data were not available due to sampling problems

Table 27: Gas Composition Profiles at Different Depths of the Columns on the 90<sup>th</sup> Day of the Experiment at a Gas Flow Rate of 10 mL/min and Air Flow Rate of 85 mL/min

Column	Depth Below Top of the Compost (cm)	CO <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CH <sub>4</sub>
1	5.1	33.6	6.9	34.6	25.0
	20.3	41.1	4.1	14.9	39.9
	35.6	44.6	2.8	10.0	42.6
	50.8	49.6	0.7	1.8	47.9
2	5.1	20.7	11.4	50.3	17.7
	20.3	NA	NA	NA	NA
	35.6	49.5	0.7	2.1	47.7
	50.8	49.3	0.7	2.0	47.9
3	5.1	48.8	0.7	2.1	48.4
	20.3	49.0	0.7	1.8	48.5
	35.6	49.8	0.7	1.5	48.0
	50.8	49.3	0.7	2.0	47.9
5	5.1	36.0	6.7	33.0	24.3
	20.3	43.1	3.1	11.4	42.4
	35.6	49.7	0.6	1.8	47.8
	50.8	49.4	0.6	1.7	48.2
6	5.1	31.6	6.2	40.8	21.4
	20.3	45.7	1.8	10.2	42.3
	35.6	48.3	1.2	4.3	46.3
	50.8	28.0	9.5	35.3	27.2
7	5.1	48.4	0.9	2.4	48.3
	20.3	49.0	0.7	1.6	48.7
	35.6	49.5	0.7	1.8	48.1
	50.8	49.5	0.6	1.4	48.5
8	5.1	48.7	0.7	1.9	48.6
	20.3	48.9	0.7	1.5	48.9
	35.6	NA	NA	NA	NA
	50.8	49.4	0.6	1.4	48.6

NA = Data were not available due to sampling problems

Table 28: Gas Composition Profiles at Different Depths of the Columns on the 121<sup>st</sup> Day of the Experiment at a Gas Flow Rate of 15 mL/min and Air Flow Rate of 85 mL/min

Column	Depth Below Top of the Compost (cm)	CO <sub>2</sub>	O <sub>2</sub>	N <sub>2</sub>	CH <sub>4</sub>
1	5.1	31.4	6.4	32.3	29.8
	20.3	NA	NA	NA	NA
	35.6	39.8	4.2	16.1	39.9
	50.8	49.3	0.6	1.9	48.1
2	5.1	26.5	9.8	43.2	20.6
	20.3	NA	NA	NA	NA
	35.6	48.7	0.6	1.9	48.8
	50.8	50.0	0.5	1.5	48.0
3	5.1	48.7	0.5	1.3	49.5
	20.3	48.8	0.6	1.4	49.2
	35.6	49.2	0.6	1.4	48.9
	50.8	49.3	0.7	2.0	47.9
5	5.1	36.0	6.7	33.0	24.3
	20.3	36.7	7.6	18.5	37.2
	35.6	48.6	0.7	2.1	48.5
	50.8	49.6	0.5	1.3	48.6
6	5.1	36.7	4.7	29.0	29.6
	20.3	44.0	2.4	9.6	43.9
	35.6	45.3	2.1	7.5	45.2
	50.8	22.3	11.4	44.6	21.7
7	5.1	48.4	0.6	1.6	49.3
	20.3	48.2	0.6	2.3	48.9
	35.6	48.7	0.7	1.9	48.7
	50.8	49.5	0.5	1.3	48.6
8	5.1	47.9	0.8	2.4	48.9
	20.3	48.8	0.6	1.4	49.3
	35.6	NA	NA	NA	NA
	50.8	50.2	0.4	1.0	48.4

NA = Data were not available due to sampling problems

Table 29: CH<sub>4</sub> Emissions for Alternate Covers During the Rainy Season (gm CH<sub>4</sub>/m<sup>2</sup>-day)

Area	0.91 m compost + wood chips	0.31 m compost + wood chips	0.91 m compost	0.31 m compost	0.91 m green waste	0.61 m green waste	0.31 m green waste	0.31 m soil
<b>Gas System at Low Vacuum (47-63 cfm)</b>								
1/23/06	21.5	0.0	0.3	14.1	3.9		0.0	23.6
1/24/06	27.8	0.0	0.2	22.4	3.2	0.3	0.0	19.1
1/24/06					5.3			9.4
1/25/06	21.9	0.0	0.1	20.3	6.8	2.0	0.0	13.5
1/25/06	21.2	0.0	0.1	23.8	9.4	0.3	0.5	1.1
1/25/06	11.8	0.0		21.5	3.6		0.4	
<b>Gas System at High Vacuum (117 cfm)</b>								
1/30/06	6.39	0.00	0.25	4.09	6.25	0.61	0.00	1.71
1/30/06	5.69	0.00		2.54	3.33			1.99
1/31/06	0.40	0.00	0.24	0.69	1.69	0.01	0.00	2.12
1/31/06	0.63	0.00	0.00	1.78	2.10	0.00	0.00	0.90
1/31/06			0.07				0.00	
1/31/06							0.00	

Table 30: CH<sub>4</sub> Emissions for Alternate Covers During the Dry Season (gm CH<sub>4</sub>/m<sup>2</sup>-day)

Area	0.91 m compost + wood chips	0.31 m compost + wood chips	0.91 m compost	0.31 m compost	0.91 m green waste	0.61 m green waste	0.31 m green waste	0.31 m soil	Side Slope green waste and shredded tires	Side Slope close to bottom, green waste only
<b>Gas System at Low Vacuum (30 cfm)</b>										
11/15/06	0	0.014	0.005	0	0.039	0.02	2.07	22.97		
11/16/06	0	0	0	0	0.037	0	3.30	1.22		
11/16/06	0	0.012	-0.013	-0.017	0	0	0.00	0.29		
11/16/06	0	0	0.010	0	0	-0.01	2.78	0.27		
11/16/06	0	0	0	0	0	0	1.84	1.52		
<b>Gas System at High Vacuum (60 cfm)</b>										
11/29/06	0.008	0	0	0	0	0	0	-0.62	0	0
11/29/06	0	0	0	0	0.051	0	2.130	1.32	0	0.90
11/30/06	0	0	0	0	0.020	0.010	2.522	2.12	0.01	1.50
11/30/06	0	0	0	-0.010	0.016	0	2.276	2.79	-0.31	1.16
11/30/06	0	-0.002	0	0	0.019	0	1.316	0	0.06	2.84