Updated Analysis of Greenhouse Gas Emissions and Mitigation from Municipal Solid Waste Management Options Using A Carbon Balance

Brian Bahor, QEP
Covanta Energy Corporation, 40 Lane Road, Fairfield, NJ 07004

Keith Weitz
RTI International, 3040 Cornwallis Road, Research Triangle Park, NC 27709

Andrew Szurgot
Stratosphere, LLC, 88 Balsam Court, Paramus, NJ 07652

ABSTRACT

Municipal solid waste (MSW) management is internationally recognized for its potential to be both a source and mitigation technology for greenhouse gas (GHG) emissions. Historically, GHG emission estimates have relied upon quantitative knowledge of various MSW components and their carbon contents, information normally obtained from MSW characterization studies. Aside from errors and costs associated with such studies, these point-in-time and location-specific data do not reflect temporal or geographic changes and are therefore limited in their utility for estimating GHG emissions related to proposed MSW management projects. This paper presents an alternative approach to estimate GHG emissions and mitigation using the concept of a carbon balance, where key carbon quantities are determined from operational measurements at modern municipal waste combustors (MWCs).

The proposed approach considers several major MWC and landfill process variables, including total carbon in MSW, CO_2 from combustion, CO_2 and CH_4 in landfill gas, landfill gas collection efficiency, and landfill carbon storage. The only variable common to both MWCs and landfills is the total carbon in MSW. In order to determine the value(s) of this important parameter, two independent procedures were used. First, the higher heating value of MSW was determined using a derivation of ASME Performance Test Code 4. Then the Boie formula was used to define a corresponding range of carbon content. Secondly, certified continuous stack emission monitoring data was used to quantify annual CO_2 emissions from a known quantity of waste, with the biogenic/non-biogenic split of stack CO_2 determined in accordance with ASTM D6866.

The results of the carbon mass balance were used as input to the Municipal Solid Waste Decision Support Tool (MSW-DST) developed by the U.S. Environmental Protection Agency (USEPA) and RTI to yield a life cycle assessment and comparison of MSW management options in the U.S. The results of the study show that the MWC scenario outperforms every landfill scenario in terms of GHG emissions, regardless of the landfill gas management technique or collection efficiency.

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) and other organizations have recognized waste management as an important sector regarding GHG emissions and mitigation potential. [1,2,3] As an example, methane from landfills is estimated to contribute on the order of 30–35 Tg of methane (CH_4) annually to the global CH_4 emission of ~550 Tg/yr.[4]

While the accuracy of a global estimate is itself uncertain, there are also uncertainties with local estimates due to a lack of knowledge about the waste composition and specifically its carbon content. The total amount of carbon in MSW and its origin, biogenic or fossil (non-biogenic), is a primary variable in understanding the GHG emission characteristics at modern municipal waste combustors (MWCs) and landfills, the two most popular management options for the MSW remaining after waste reduction, reuse and recycling.

The purpose of this paper is to establish a more robust technique for determining the carbon content of MSW and to use those results in a life cycle assessment that determines the GHG impacts of modern MWCs and landfills. The results of this analysis have direct application to federal and state agencies establishing GHG inventories. The approach presented herein can also be adopted and used by municipalities that operate or own either a modern MWC or landfill. Figure 1 and Table 1 describe the general approach and major process streams.

Figure 1 – Illustration of Simplified Carbon Balance

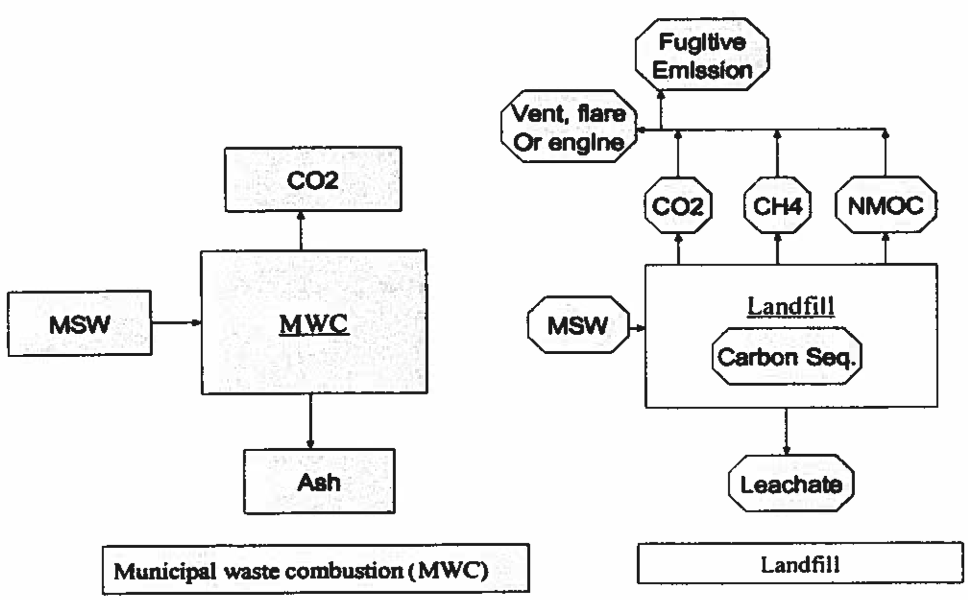


Table 1. Process Streams Containing Carbon

Management Option		Process Stream	Comment
MWC	1	Carbon in MSW	Variable
	2	Carbon in ash residue	Constant
	3	Stack CO_2	Variable
	4	Stack CO	Negligible
Landfill	1	Carbon in MSW	Variable
	2	Carbon in leachate	Negligible
	3	Carbon in LFG CO_2	Constant
	4	Carbon in LFG CH_4	Constant
	5	Carbon in LFG NMOC	Negligible
	6	Landfill gas collected for flare or engine	Variable
	7	Fugitive emissions	Variable
	8	Carbon storage	Variable

CO = carbon monoxide
NMOC = non-methane organic compounds
LFG = landfill gas

The initial analysis identified four carbon-containing process streams around a MWC and eight around a landfill; however, upon a review of literature and an estimate of carbon losses in each process stream, the list can be reduced to three carbon-containing process streams for a MWC and six for a landfill. The carbon-containing process streams retained for the analysis are identified as a variable or constant in the comments column in Table 1.

METHODS FOR DETERMINING CARBON CONTENT

Traditional Approach

Scientific determination of solid waste composition and quantities is an important step in the development of municipal waste programs, including recycling and composting.[5] Unfortunately, field characterization programs are expensive with the results having limited application because the scope of the program does not necessarily reflect a variety of variables such as the location (urban, suburban, rural), dwelling type (multi-family, single dwelling), seasonal (wet, dry, spring, fall), and temporal factors (cultural habits, changing recycling behavior, etc.). One short-term evaluation determined that 200 random samples were necessary to provide a 95% confidence level of the MSW categories as a snapshot MSW characterization with each sample being at least 200 lbs.[6] This sampling effort is only to identify the composition according to traditional categories (percent paper, plastic, glass, etc.) and did not include the effort to establish the chemical composition of the waste.

In addition to significant cost savings, the proposed approach of using MWC operational measurements has certain advantages including the use of precise and accurate instruments that are routinely calibrated and that all results are from a significantly larger amount of MSW with data representing various locations, under various weather conditions and over long periods of time.

Municipal Waste Combustion Facilities– The Alternative Approach

Determination of Higher Heating Value (HHV)

The higher heating value (HHV) of MSW is an important parameter in designing and operating an MWC facility and consequently has been studied in depth. Calculation procedures to measure the HHV are based on the boiler-as-a-calorimeter concept that includes the heat loss method for boiler efficiency determination contained in American Society of Mechanical Engineers (ASME) Power Test Code (PTC) 4, portions of the input-output method and various equations and assumptions all combined into one cohesive test calculation method.[7] This derivation of PTC 4 has been in use for many years and is the basis of PTC 34-2007 that was approved and adopted by ASME that is currently under review by the ASME.

Determination of MSW HHV uses information for a variety of parameters that are continuously monitored and recorded. A partial list of the parameters, the instrument used in the measurement and the basis for that instrument being calibrated or certified is provided in Table 2.

Table 2. List of Major Parameters Used in determining MSW HHV

Parameter	Instrument	Calibration/Certification
MSW Feed	Scale house weigh scales	Quarterly
Feedwater temperature and pressure	Transmitters	Semi-annual
Steam generation rate	Steam flow meter	Per USEPA
Steam temperature and pressure	Transmitters	Semi-annual
Combustion air flow	Venturi-transmitters	Semi-annual
Economizer exit temperature	Thermocouples/transmitters	Semi-annual
CO_2, O_2, in flue gas	Certified continuous emission monitors	USEPA 40 CFR Part 60 Appendix B and F

The same derivation of PTC 4 has been applied to the majority of MWC facilities operated by Covanta Energy Corporation for the last ten years with slight modifications being used in prior years. Figure 2 presents the frequency distribution of annual HHV values from 22 facilities. Annual HHV values are considered to be more reliable than those collected over shorter periods because changes in the MSW inventory at the facility are much smaller than the MSW throughput as measured by the truck weigh scales. Information needed for the annual HHV values is also subject to increased scrutiny due to its inclusion in reports to clients and environmental agencies are also on an annual basis. A carbon balance for estimating GHG mitigation potential is a long-term issue that warrants long-term values from actual operations as described above.

The annual HHV values exhibit a normal distribution with the mean and median being almost identical. A review of the data demonstrates that 90% of the annual average HHV values are between 4646 and 5642 Btu/lb.

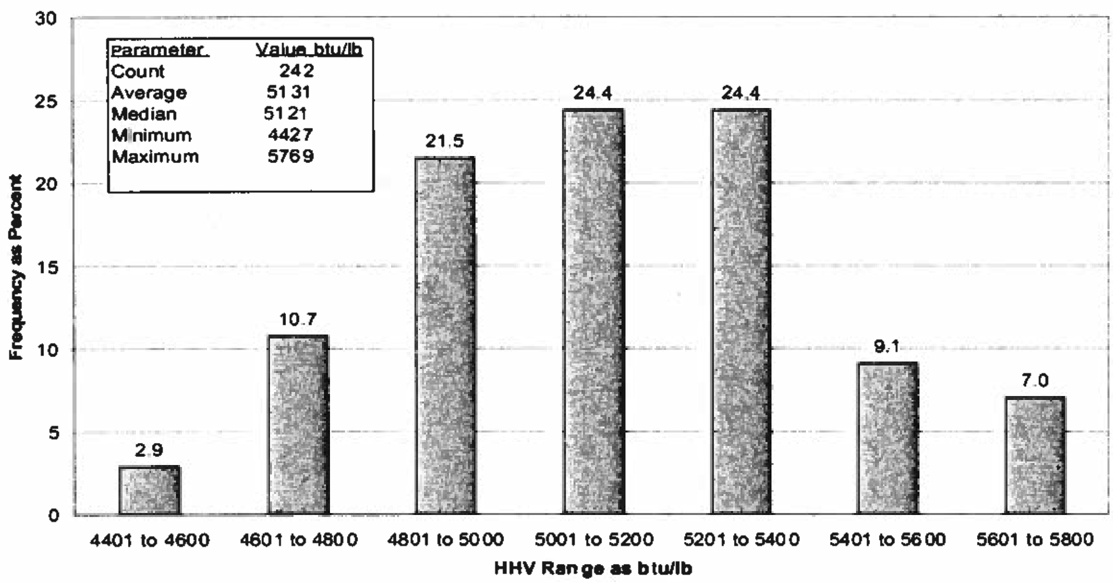
The Boie formula is most often used to correlate the ultimate analysis of MSW to its HHV and was used to estimate the carbon content that would correlate with the above range.[8] The Boie formula is provided as Equation 1:

Eqn 1 :

$$HHV = \%H_2*(495.27) + \%C*(149.76) + \%S*(45) + \%N_2*(27) + \%Fe*(21.96) + \%Cl*(16.92) + \%Fl*(33.3) - \%O_2*(46.44)$$

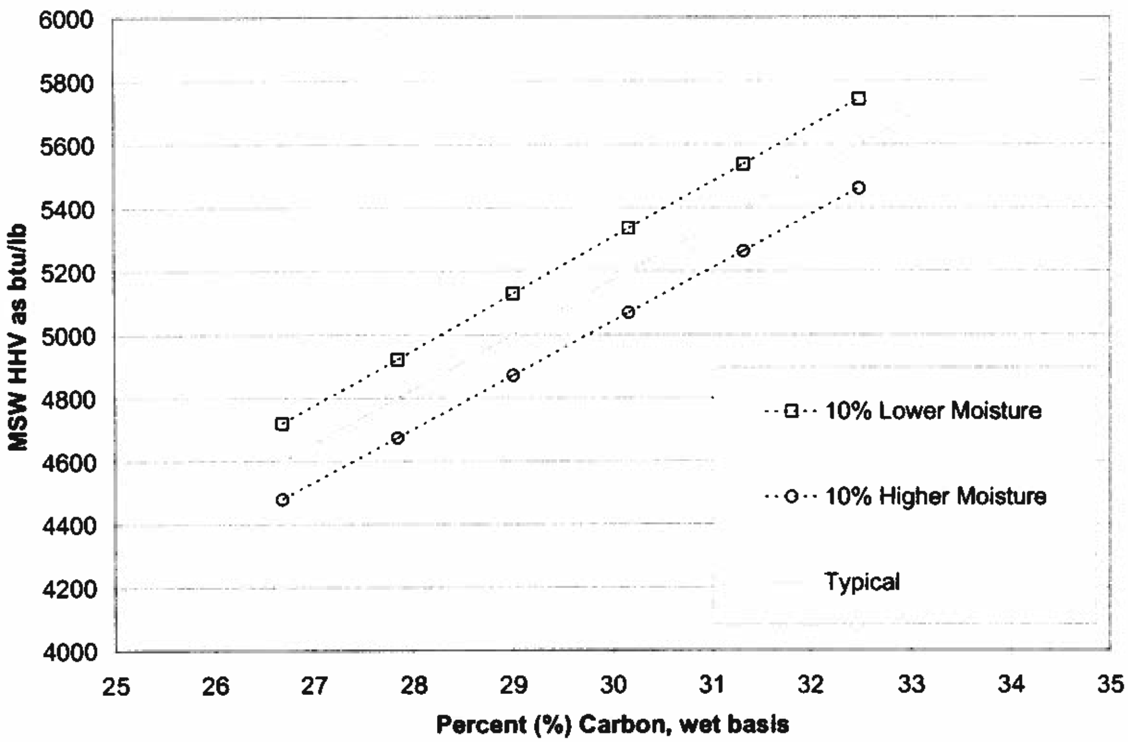
The value of individual components is the actual weight percent on a wet basis.

Figure 2. Frequency Distribution of Annual HHV Values from 1996 to 2006



While there are an infinite number of waste analyses that could generate a given HHV, the analysis started with an assumed analysis based on industry experience and made adjustments to the carbon, hydrogen and moisture content to establish a range of potential carbon content for each HHV. Figure 3 illustrates the potential range of carbon content that coincides with the reported annual MSW HHV. The range of carbon on a wet weight basis ranges from 27% to 33%. Because moisture content has a significant impact on the HHV of MSW, a range from 10 to 30 % was considered with an average value of 20 %.

Figure 3. MSW Higher Heating Value (Btu/lb) as a Function of Carbon and Moisture Content



Total Carbon Content of MSW

The total carbon content of carbon in MSW is typically presented as a singular value that is not correlated to a specific time or location. Sample specific values as high as 52% on a dry basis (43% wet basis) have been reported and are considered to be very high relative to reported annual averages and while possible for a short-term localized situation, it does not appear to be representative for regional or U.S. applications. The total carbon content of MSW in other countries has been reported to be quite different with a range of 15.74 to 29.67 weight percent being identified for Taiwan.[9] In general, the total carbon content is understood to be a variable that is dependent on many parameters such as local separation efforts or even national efforts such as European Directive 1999/31/EC that requires reduced landfilling of biodegradable MSW.

While the above discussion provides the technical basis for establishing a possible range for carbon content, a direct estimate of total carbon content can be determined through the use of two instruments at MWC facilities, 1) the weigh scale used to report MSW accepted at the facility, and 2) the certified continuous emission monitoring system (CEMS). The weigh scale is typically calibrated on at least a quarterly frequency with the results being submitted to environmental agencies in compliance reports and to municipal clients in commercial reports. The stack CEMS data is calibrated on a daily basis and audited quarterly. The total annual mass emission rate of stack CO_2 can de determined from EPA Method 19 which is commonly used to determine mass emission rates of regulated pollutants in accordance with Appendices B and F of 40 CFR Part 60. Equation 2 provides the basis for this alternative approach:

Eqn 2: % C (wet basis) = [CO_2 (ton per year) * 12/44] / MSW (tons per year)

Where:

CO_2 (TPY) : Annual emission factor of CO_2 as determined by CEMS
MSW (TPY) : Annual combustion rate of MSW as determined by weigh scales

Operating data from four facilities is provided in Table 3 to demonstrate this approach. Table 3 also includes the minor impact of carbon in combustion residue.

Table 3. Total Carbon Content of MSW Using Annual Stack CEMS and MSW Inventory Data

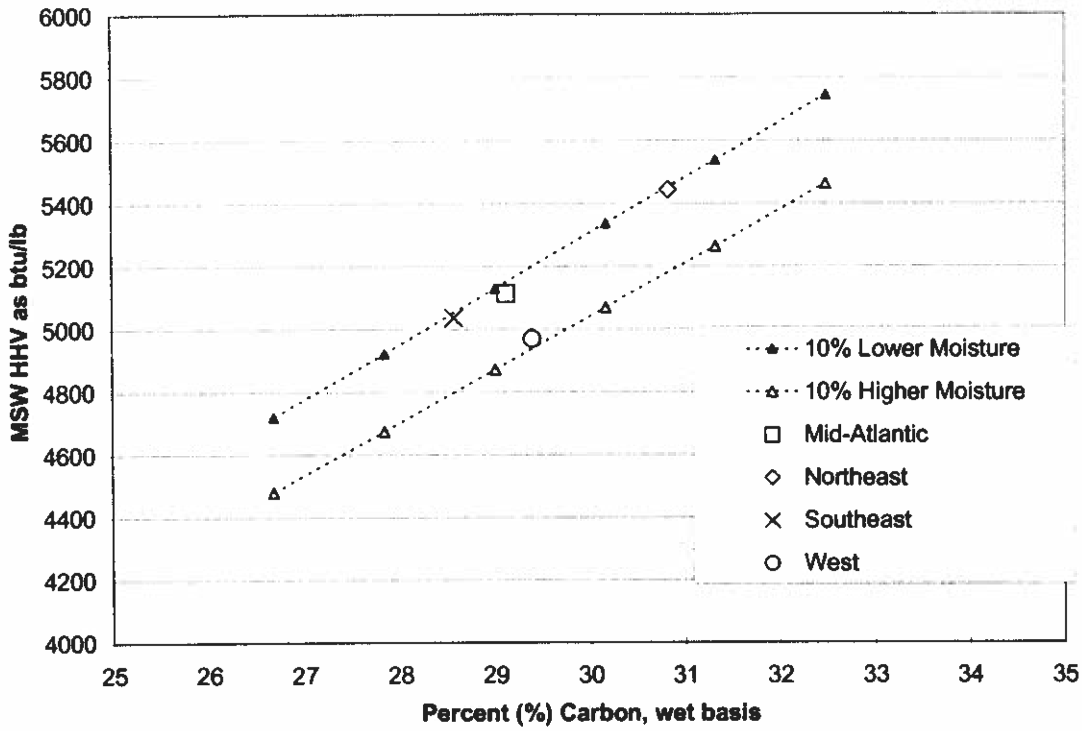
Facility	CO_2 (TPY)	MSW (TPY)	Calculated Carbon (1)	Total Carbon (2)	HHV (BTU/lb)
Northeast	212,980	189,980	30.6	31.1	5442
Mid-Atlantic	367,640	347,380	28.9	29.4	5113
Southeast	353,960	340,990	28.3	28.8	5036
West	259,740	243,150	29.1	29.6	4969

(1) Calculated carbon by Eqn. 2
(2) Total carbon = Calculated carbon + 0.50 % carbon in ash

Comparison of Fuel Window with Calculated Results

Figure 4 is the same as Figure 3 except that the four total carbon estimates from Table 3 have been directly applied to enable a graphical comparison of the results from these two methods. The consistent results from the two methods validates the general range for total carbon content while also providing two separate methods to evaluate other site specific conditions.

Figure 4. Comparison of Measured Facility Data Against Predicted MSW Higher Heating Value (Btu/lb) as a Function of Carbon and Moisture Content



Measurement of Biogenic/Fossil Carbon Split

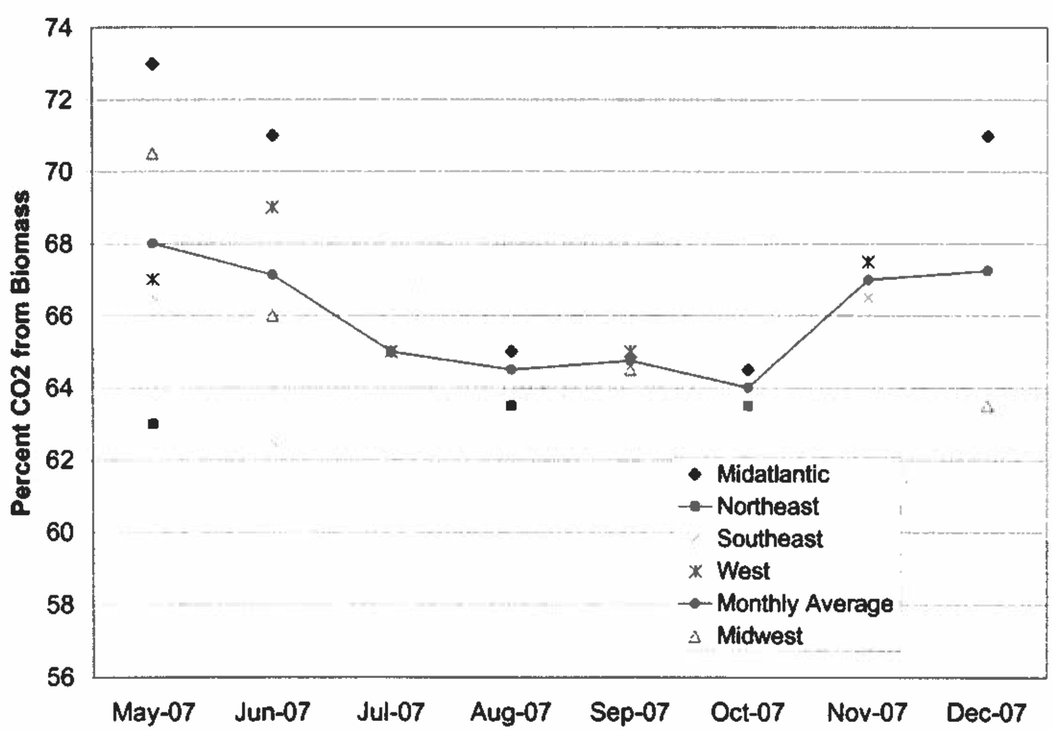
The total amount of CO_2 in stack flue gas from the combustion of MSW is comprised of two components: CO_2 from biogenic (biomass) and CO_2 from anthropogenic (fossil) components. Flue gas samples from full scale MWC facilities were analyzed according to ASTM-D6866 to derive the biogenic CO_2 content. ASTM-D6866 is based on the same concepts used by the U.S. Department of Agriculture to derive bio-based content of manufactured products containing carbon.[10] This method determines the amount of biogenic CO_2 by comparing the relative amount of radiocarbon (C14) to a modern reference standard. The California Air Resources Board (CARB) and the European Union Emissions Trading System recognize this procedure in determining stack CO_2 characteristics.

Five facilities were selected to evaluate variability due to time and location. The goal was to secure two integrated flue gas samples on a monthly frequency from the same continuous emission monitoring systems used in determining the total CO_2 concentration and emission rate. Field sampling used a rotameter to fill a Tedlar® sample bag over an approximate 2-hour period with the sample being shipped directly to Beta Laboratories for analysis. Table 4 presents the results from four regions and Figure 5 presents the results over a multi-month sampling program.

Table 4. Percent Biogenic CO_2 Results per ASTM-D6866

Month 2007	Facility Information					
	Mid-Atlantic	Northeast	Midwest	Southeast	West	Monthly Average
May	73	63	71	67	67	68
June	71		66	63	69	67
July					65	65
August	65	64		65		65
September			65		65	65
October	65	64				64
November				67	68	67
December	71		64			67
Mean	69	63	66	65	67	66
+ 3 %	72	66	69	68	70	69
- 3 %	66	60	63	62	64	63

Figure 5 – Biomass CO_2 Trend from ASTM D6866



Each monthly value in Table 4 and Figure 5 is the mean of two samples. The absence of a complete monthly data base prevents any conclusion regarding variability over time on a short-term basis; however, the nationwide monthly average does not indicate any significant variation over the 8 month sampling period.

LIFE CYCLE ASSESSMENT

Municipal Solid Waste Decision Support Tool (DST)

The Municipal Solid Waste Decision Support Tool (MSW-DST) computer model was developed by RTI in cooperation with the U.S. Environmental Protection Agency (EPA) Office of Research and Development. The MSW-DST computer model has undergone extensive stakeholder input and peer review (as well as a separate peer review by EPA), and is regarded as a cutting-edge software tool that can help solid waste planners make more informed decisions. The MSW-DST has been used to analyze the energy and environmental impacts of different MSW management scenarios in prior papers.[11, 12, 13, 14] These analyses have typically considered a waste shed with a variety of concurrent options such as composting, recycling, landfilling and MWC and have not specifically considered the simpler comparison of the two post reduction-reuse-recycling options, landfills and MWCs. However, these same analyses have concluded that MWCs provide the best GHG mitigation potential for MSW after reduction, reuse and recycling.

The purpose of this analysis is to use total carbon and its biogenic/fossil fraction to analyze in greater detail the difference between landfills and MWCs. Table 5 identifies key variables considered in this analysis. The MWC industry provides for the disposal of approximately 29 million tons of MSW per year. This value was used in the DST with the objective of estimating the nationwide impact to GHG emissions and to also enable the derivation of unit emission factors.

With sound values for both total carbon and percent biogenic carbon as described earlier, two landfill parameters have a large impact on the calculation of GHG emissions and/or mitigation potential; 1) the amount of methane generation per megagram of MSW (L_o) of landfilled MSW, and the landfill gas collection efficiency. Both of these landfill parameters have significant uncertainty. For the purpose of comparing landfill and MWC management options, both of these landfill parameters were evaluated over a range as described below.

Table 5. Key Assumptions Used in Analysis.

Parameter	Assumption
General	
Waste Generation	29 million tons
Waste Composition	National Average – post recovery [a]
Waste Collection Frequency	1 time per week
Transportation Distances	
Collection to WTE Facility or Landfill	10 miles one way
WTE Facility to Ash Landfill	10 miles one way
WTE Facility	
Basic Design	Mass Burn
Heat Rate	18,700 BTU/kWh
Waste Input Heating Value	5100 BTU/lb MSW
Percent biogenic CO2	66
Metals Recovery Rate	70%
Utility Sector Offset	Offset is coal, oil, and natural gas power production based on national average fuel mix
Landfill	
Basic Design	Subtitle D
Time Period for Calculating Emissions	100 years
Landfill Gas Generation	100 and 170 m^3 CH_4/Mg MSW
Global Warming Potential for methane	21
Lifecycle Landfill Gas Collection Efficiency [b]	0, 25, 35, 45, 55, 65 and 75%
Methane oxidation by landfill cover material	10 %
Landfill Gas Management	Vent, LFG collection with flare or energy recovery
Utility Sector Offset	Offset is coal, oil, and natural gas power production based on national average fuel mix

[a]From EPA's Office of Solid Waste 2005 Waste Characterization for the United States.
[b]Gas collection efficiency in an integrated average that reflects different collection effectiveness occurring during the periods of landfill development.

Methane Generation Potential. L_o

Table 6 provides an overview of reported Lo values and the potential range for this parameter. An independent literature review[15] of L_o values did not reveal any full scale long-term studies that considered both collected and fugitive emissions of landfill gas. The most frequently cited L_o factor is approximately 100 m^3/Mg MSW including citations in LandGem[16], AP-42[17] and a survey by the U.K. Department of Food and Rural Affairs (DEFRA).[18] The lowest L_o value is approximately 70 m^3/Mg and it is used in the WARM model, however this value appears to be from a bench-scale laboratory study[19] which had the results adjusted to yield the 156 m^3/Mg value referenced by the USEPA. Because the objective of this analysis is to establish an understanding of GHG emissions and mitigation potential, EPA's L_o value of 100 and 170 m^3/Mg has been selected because it brackets EPA data. The carbon in CO_2 is based on the amount of CO_2 in landfill gas. For this analysis, the EPA default ratio of CO_2 to CH_4 of 50:50 was used.

Table 6. Survey of International Lo Values

Source	L_o (m^3 CH_4 / Mg MSW)
Typical MSW - theoretical	400 – 520 [24]
Organic degradability - theoretical	100 – 310 [24]
USEPA – Potential to Emit	170
USEPA – Solid Waste and GHG Report	156
USEPA – GHG Inventory	100
USEPA – WARM	70
DEFRA Average [20]	110

Landfill Gas Collection Efficiency

The landfill gas collected and fugitive landfill gas emission factor are linked by the integrated landfill gas collection efficiency. While there have been an abundance of papers that cite the 75 % EPA default value as being conservatively low, an independent review of available literature[21] does not show any significant field program that considers landfill gas collection performance during all phases of landfill operation. Conversely, a review of sixteen case studies provided by the USEPA through its Landfill Methane Outreach Program (LMOP) identified only 4 landfills with actual LFG collection efficiencies while the other twelve landfills assumed a landfill gas collection efficiency. The 2006 IPCC guidelines[22] includes default values as low as 20% and references measurements between 10% and 85% at gas recovery projects and 10% and 80% at closed landfills. These values are consistent with a range of LFG collection efficiency between 35% and 85% reported by Spokas et al.[23]

Integrated Landfill Gas Collection Efficiency

The landfill gas collection efficiency can vary significantly during different operating phases of a landfill. An integrated landfill gas collection efficiency range of 25% to 75% was considered in this study to recognize the uncertainty in this influential parameter and the various gas collection efficiencies during various operating periods over the 100 year or longer anaerobic decomposition.

Table 7 provides several examples on how the life cycle landfill gas collection efficiency is calculated when considering five operating phases at a landfill. The landfill gas efficiency is applied to the percent of methane predicted by the 1st order model for each phase. Scenario 7 illustrates the necessary LFG collection efficiency during each phase to approach the default 75% LFG collection efficiency used in many papers.

Table 7. Integrated Landfill Gas Collection Efficiency

Landfill Information			Landfill Gas Collection Scenarios						
Phase	Years	% CH_4	1	2	3	4	5	6	7
1	3	14	0	0	0	0	0	0	35
2	7	25	12	25	35	35	50	65	75
3	10	24	25	50	50	75	75	75	90
4	30	29	50	50	75	90	90	90	90
5	50	8	0	0	0	0	0	0	0
Total	100	100	23	33	42	53	56	60	71

Evolution of methane from landfills is widely predicted using the 1st order gas generation model including by EPA's LandGEM.[24] The percentage of methane generated during each of the five phases of the landfill in Table 7 are based on equation 3 below, which is derived from the definite integral of the 1st order rate equation used by LandGEM.

Eqn 3: $\% \, CH_4 \; generation = 100\% \cdot \left(e^{-k\tau_1} - e^{-k\tau_2}\right)$

Where:

k = Anaerobic decay rate constant (yr^{-1}) = 0.05 yr^{-1} [25]

τ_1 = Time in years since beginning of methane generation from mass of MSW to start of landfill period

τ_2 = Time in years since beginning of methane generation from mass of MSW to end of landfill period

Anaerobic waste degradation and the corresponding emissions predicted by the 1st order decay rate equation begin in the year *following* the placement of the waste in the landfill. The timeframes outlined in Table 7 are from the beginning of methane generation, which are offset one year from the placement of waste in the landfill. For example, the end of Phase 1 corresponds to four years after the initial placement of waste in the landfill, and one year from the beginning of methane generation predicted by the 1st order decay model.

Soil Oxidation

Soil oxidation of methane was not identified as a specific carbon containing process stream, however it must be considered in the determination of a carbon balance. There are also numerous papers and opinions on the appropriate soil oxidation factor for CH_4 with a wide range representing soil cover quality, temperature, moisture content and others. This analysis uses the EPA default value of 10% which is consistent with the IPCC default value for well managed sites but conservative relative to the IPCC default value of 0% for other sites.[26]

RESULTS AND DISCUSSION

The MSW-DST was run for two general scenarios, MWC and Landfill with the landfill scenario including three general designs. The labeling convention used in all results is CO_2 equivalence (CO_2E) using the Global Warming Potential (GWP) of 21 for methane. If the IPCC GWP factors for methane from the 4th Assessment Report were used (GWP of 25 for 100 years and 72 for 20 years), the results for avoided methane would increase.

Municipal Waste Combustion

The MWC scenario considered 29 million tons being managed by an average MWC facility. This condition yielded a GHG mitigation result of -2.18 million MTCE which is equivalent to an emission factor of -0.30 tons of CO_2E per ton of MSW combusted. The "negative" emission factor is due to the amount of avoided CO_2 from electrical generation and metals recovery being greater than the emissions factor for fossil CO_2. The "negative" emission factor establishes that MWC is a GHG mitigation process as a MSW disposal option.

Landfill

Table 8 presents the unit emission factors for three landfill scenarios (vent, flare, internal combustion engine) and the two Lo factors, 100 and 170 for the full range of integrated landfill gas collection efficiencies.

Table 8. Life Cycle Greenhouse Gas Unit Emission Factors for Landfill Scenarios

LFG Collection (%)	GHG Emissions(Tons CO_2E/ ton MSW)					
	Vent Scenario		Flare Scenario		ICE Scenario	
	Lo=100 scm CH_4/Mg	Lo=170 scm CH_4/Mg	Lo=100 scm CH_4/Mg	Lo=170 scm CH_4/Mg	Lo=100 scm CH_4/Mg	Lo=170 scm CH_4/Mg
0	1.31	2.20	-	-	-	-
25	-	-	1.00	1.66	0.92	1.53
35	-	-	0.87	1.45	0.76	1.26
45	-	-	0.74	1.23	0.60	1.00
55	-	-	0.61	1.01	0.45	0.73
65	-	-	0.49	0.80	0.29	0.46
75	-	-	0.36	0.58	0.13	0.19

Life Cycle Assessment: A Comparison of MWC and Landfill

Table 9 presents the life cycle assessment results for the case where MSW is disposed in a MWC instead of a landfill. Table 9 demonstrates that the MWC option promotes a reduction in GHG emissions and is a GHG mitigation technology. The amount of GHG mitigation depends on the type of landfill, the amount of methane generation and the amount of landfill gas collected and destroyed. While the primary focus of this assessment is to consider the difference between MWC and various landfill scenarios, the results can also be used to estimate the different GHG emission characteristics between different landfill scenarios.

Table 9. Life Cycle Greenhouse Gas Emissions for MWC versus Landfill Scenarios [a,b]

LFG Collection (%)	(Tons CO2E/ ton MSW)					
	Vent Scenario		Flare Scenario		ICE Scenario	
	Lo=100 scm CH_4/Mg	Lo=170 scm CH_4/Mg	Lo=100 scm CH_4/Mg	Lo=170 scm CH_4/Mg	Lo=100 scm CH_4/Mg	Lo=170 scm CH_4/Mg
0	-1.62	-2.51	-	-	-	-
25	-	-	-1.30	-1.97	-1.22	-1.84
35	-	-	-1.17	-1.75	-1.07	-1.57
45	-	-	-1.05	-1.53	-0.91	-1.30
55	-	-	-0.92	-1.32	-0.75	-1.03
65	-	-	-0.79	-1.10	-0.59	-0.76
75	-	-	-0.67	-0.89	-0.43	-0.49

Notes: [a] Each value is the net difference between the EfW emissions value (-0.30 ton CO2E/ton MSW) and the designated landfill scenario emissions value.
[b] Negative value indicates avoided emission.

Table 10 presents the results when the unit emission factors from Table 9 are assigned to two nationwide distributions of landfills to estimate a nationwide life cycle assessment factor. The baseline landfill distribution is 50/25/25 indicating that 50% of MSW is managed at landfills without landfill gas collection, 25% is disposed at landfills with landfill gas collection and flares and the last 25% is disposed at landfills with landfill gas collection and an energy recovery system, in this case an internal combustion engine. The second distribution of 40/30/30 provides an indication of the impact as more landfills use landfill gas collection.

Table 10. Nationwide Life Cycle MWC Greenhouse Gas Emission Factors Versus Landfill Blend Scenarios.

LFG Collection (%)	(Tons CO2E/ ton MSW)			
	Landfill Allocation 50/25/25[b]		Landfill Allocation 40/30/30[c]	
	Lo=100 scm CH_4/Mg	Lo=170 scm CH_4/Mg	Lo=100 scm CH_4/Mg	Lo=170 scm CH_4/Mg
25	-1.44	-2.20	-1.40	-2.14
35	-1.37	-2.08	-1.32	-2.00
45	-1.30	-1.96	-1.23	-1.85
55	-1.23	-1.84	-1.15	-1.71
65	-1.16	-1.72	-1.06	-1.56
75	-1.08	-1.60	-0.98	-1.42

Carbon Storage

Carbon storage (sometimes referred to as sequestration) in the context of sold waste disposal is the potential long-term storage of carbon in a landfill. Only organic matter is considered to be eligible for carbon storage; components that are based on fossil carbon, such as plastics and textiles, are not considered as stored because they are simply being transferred from one carbon stock (an oil field) to another.

Results provided in this paper have shown that there is a reasonably wide range of HHV and associated carbon content for MSW in the U.S. as an annual average. It is reasonable to expect that the variability of HHV and carbon content would be larger on a short-term basis due to a variety of parameters such as local demographics, weather, cultural habits and others. Table 11 describes the approach used to estimate the potential carbon storage value for MSW with Table 12 providing the results. Figure 6 illustrates the proposed range of stored carbon as a function of total carbon and the fossil – biomass split presented of 34/66. The estimated carbon storage value ranges from 0.08 to 0.12 ton C/ton wet MSW for Lo = 100 and 0.008 to 0.048 ton C/ton wet MSW for Lo = 170.

Table 11. Carbon Storage Calculations Using a Carbon Balance

Variable	Variable	Comment
A	Total Carbon	Range associated with documented MSW HHV
B	Carbon lost as gas	Subtract amount of CO_2 and CH_4 associated with a Lo = 100 for typical conditions and a Lo = 170 for maximum methane generation potential.
C	Fossil Carbon that does not meet definition of carbon sequestration	Subtract the average fraction of fossil carbon (34 %) as indicated by field data using ASTM 6866 results.
D = A-B-C	Residual carbon available for carbon sequestration	Maximum possible amount of carbon that could be sequestered ignoring any amount lost as carbonates in leachate or other leakage.

Table 12. Carbon Sequestration Estimates Using Nationwide Variations in MSW Composition

Parameters & Units								
Parameter	Units	Carbon Weight %, Wet Basis						
Total C	%	27	28	29	30	31	32	33
	Ton C / Ton MSW	0.27	0.28	0.29	0.30	0.31	0.32	0.33
Fossil C	%	34	34	34	34	34	34	34
	Ton C / Ton MSW	0.092	0.095	0.099	0.102	0.105	0.109	0.122
Carbon Storage								
Lo = 100	Ton/Ton (a)	0.078	0.085	0.091	0.098	0.105	0.111	0.118
Lo = 170	Ton/Ton(a)	0.008	0.015	0.021	0.028	0.035	0.041	0.048

(a) The amount of carbon in CO_2 and CH_4 is a constant for each condition. For Lo = 100, the C in CO_2 = 0.05 and the C in CH_4 = 0.05. For Lo = 170, the C in CO_2 = 0.085 and the C in CH_4 = 0.085.

Figure 6. Potential Carbon Storage as a Function of Total Carbon Content

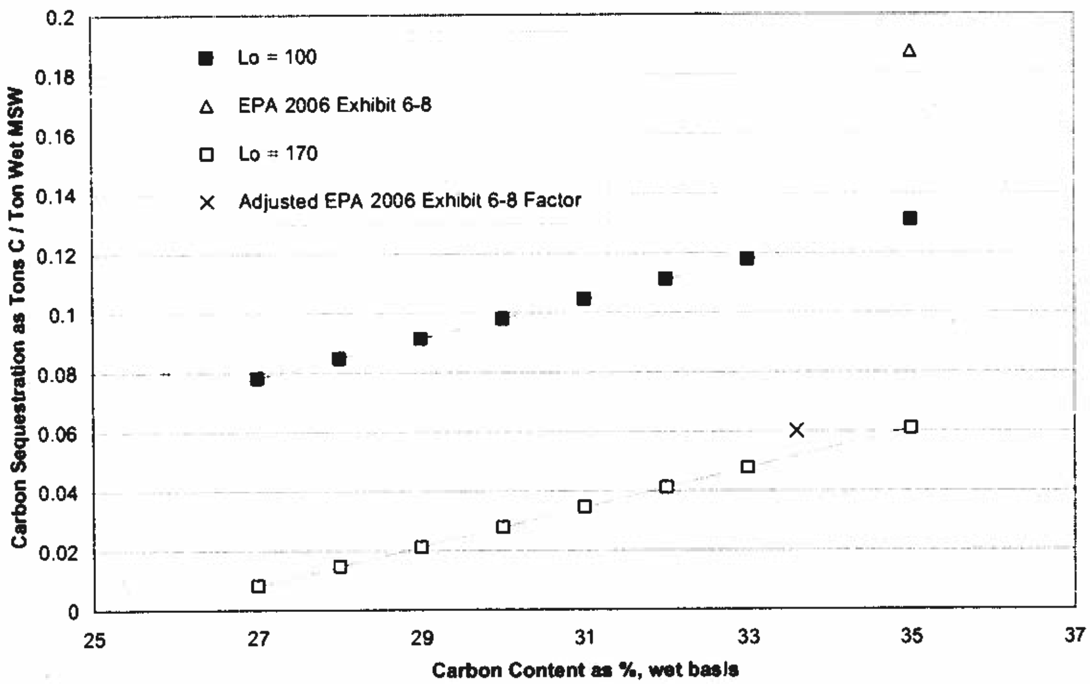


Figure 6 also shows the landfill carbon storage factor (0.17 MTCE/ton wet MSW or 0.19 ton C/wet ton mixed MSW) presented in USEPA's life cycle report, [25] a value that is significantly greater than the long-term carbon values presented in this paper. An examination of USEPA's calculations revealed two issues that account for this difference. First, USEPA's value mistakenly includes fossil carbon, as was recently confirmed.[27] Second, USEPA converts laboratory data from dry basis to 35% wet basis using a mixed MSW moisture content of 16%, a value lower than is typical. Correcting for these issues by removing fossil carbon (assumed to be 34 % of total wet carbon) and using 20% moisture, USEPA's factor becomes 0.06 ton C/ton wet MSW at a carbon content of 33.6%, within the range projected using a carbon balance.

The IPCC has identified the uncertainty in estimating carbon storage with specific comment being made on the difficulty in replicating real solid waste disposal conditions in experimental studies. The annual average values found at full scale MWCs provides a more robust set of data than a small sample from one local sample program.

CONCLUSIONS

The conclusions are organized into two main areas.

MWC as an Instrument for Measuring Carbon Content of MSW

- MWC facilities are equipped with an extensive set of instruments that are used for regulatory reporting purposes and/or demonstration of compliance with contractual parameters. Two independent methods using facility data yielded consistent results for total carbon content. The first method used a derivative of ASME Power Test Code 4 and the Boie formulae. The second method used facility operating data from the continuous emission monitoring system and the weigh scales.
- ASTM Method 6866 is a demonstrated and proven technique for determining the whether CO_2 is from biogenic or fossil-based waste components.
- The estimated range of total carbon (27 to 33 weight percent) and its biogenic (66%) and fossil (34%) fraction demonstrates the possible range of carbon in MSW. These ranges are considered to be more representative of a heterogeneous fuel than any single value obtained from a short-term MSW field sampling program.

Comparison of GHG Mitigation by MWC and Landfills

- The Municipal Solid Waste Decision Support Tool is a peer reviewed lifecycle assessment (LCA) that provides valid and useful results for evaluating green house gas emissions from different municipal solid waste disposal options.
- A comparison of LCA results from municipal waste combustion (MWC) and various landfill designs shows that MWC provides superior GHG mitigation, primarily due to the generation of more electrical power and avoidance of fugitive methane emissions from landfills.
- The large amount of high caliber information from MWC facilities provides a high degree of confidence in it's GHG mitigation through avoidance of fossil fuel CO_2 and separation of ferrous metals for subsequent recycling.
- The absence of long-term studies that demonstrate actual landfill gas emission generation and control values creates uncertainty in both the actual emissions of a landfill and that avoided by an MWC facility.
- A range of landfill gas collection efficiencies is warranted to understand the potential emission characteristics of any one location unless there are long-term studies in place for all landfill operating phases and/or there are enforceable permit emission limits that include compliance demonstration with USEPA test methods.

RECOMMENDATIONS

The greenhouse gas emissions and/or mitigation potential of solid waste options should be evaluated through the use of a life cycle assessment (LCA); however, the results from a LCA or any analysis for that matter, is dependent on the quality of input data. While there are many important variables, any analysis must consider the total amount of carbon and the split between biogenic and fossil carbon. Technical information from modern municipal waste combustors demonstrates that there is variability in the total carbon content of MSW and to a certain degree, some minor variation in the biogenic/fossil split. The variability in total carbon and the biogenic/fossil split must be considered when conducting an analysis of GHG emissions and/or mitigation. If waste compositional analyses are used instead of MWC data, the estimated total carbon content and its biogenic/fossil split should be considered relative to the results presented therein.

REFERENCES

[1] Intergovernmental Panel on Climate Change (IPCC), "2006 IPCC Guidelines for National Greenhouse Gas Inventories", Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T and Tanabe K. (eds). Published:IGES, Japan.

[2] Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. Official Journal of the European Communities. July 16, 1999.

[3] USEPA Office of Solid Waste 2006, Solid Waste Management and Greenhouse Gases, A Lifecycle Assessment of Emissions and Sinks, 3rd Edition, September 2006.

[4] Matthews, E, Themelis, N.J., "Potential for Reducing Global Methane Emissions From Landfills", 2000-2030, Proceedings Sardinia 2007, Eleventh International Waste Management and Landfill Symposium.

[5] Martin, John H., Collins Alan R., Diener, Robert G., "A Sampling Protocol for Composting, Recycling, and Re-Use of Municipal Solid Waste", Journal, November, 1995.

[6] Sfeir H., Reinhart D., McCauley-Bell P.R., An Evaluation of Municipal Waste Composition Bias Sources, Journal Air & Waste Management Association. 49:1096-1102. September 1999.

[7] Semanyshyn Z., DeDuck S.,"Long-Term HHV Determination of Municipal Solid Waste – A Practical Approach".

[8] C.C. Lee, Handbook of Environmental Engineering, McGraw Hill Professional, Published 2000. ISBN 0070381836.

[9] Juin-I Liu, Rajendra D. Paode, Thomas M. Holsen "Modeling the Energy Content of Municipal Solid Waste Using Multiple Regression Analysis" 1996.

[10] Standard test Methods for Determining the Biobased Content of Natural Range Materials Using Radiocarbon and Isotope Ratio Mass Spectrometry Analysis, ASTM Designation D 6866 – 06, Copyright by ASTM International October 16, 2006.

[11] Thorneloe S., Weitz K.A., Nishtala Subba R., Yarkosky S., and Zannes M.,. The Impact of Municipal Solid Waste Management on Greenhouse Gas Emissions in the United States, Air & Waste Management Association. 52:1000-1011. September 2002.

[12] Thorneloe S., Weitz K.A., "Sustainability and Waste Management".

[13] Thorneloe S., Weitz K.A., and Janbeck J., Moving From Solid Waste Disposal to Materials Management in the United States, Tenth International Waste Management and Landfill Gas Symposium, 2005.

[14] Thorneloe S., Weitz K.A., Jambeck J., Application of the U.S. Decision Support Tool for Materials and Waste Management, Waste Management 27 (2007) 1006-1020.

[15] Personal communication with Priscilla Ulloa, Columbia University.

[16] Landfill Gas Emissions Model (LandGEM) Version 3.02 Users Guide. U.S. Environmental Protection Agency. EPA-600/R-05/047

[17] Emission Factor Documentation for AP-42 Section 2.4 Municipal Solid Waste Landfills, U.S. Environmental Protection Agency, November 1998.

[18] "Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes". Department for Environment, Food and Rural Affairs (DEFRA), March 2004.

[19] Eleazer, William E., Odle, William S., Wang, Yu-Sheng, and Barlaz, M.,"Biodegradability of Municipal Solid Waste Components in Laboratory-Scale Landfills", Environmental Science and Technology (1997) 31, 911-917.

[20] Review of Environmental and Health Effects of Waste Management: Municipal Solid Waste and Similar Wastes. DEFRA, March 2004. Enviros Consulting and University of Birmingham. Published by The Department of Environment and Rural Affairs. March, 2004.

[21] Various personal communications with Priscilla Ulloa, Columbia University.

[22] 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 3, Solid Waste Disposal.

[23] Spokas K., Bogner J., Chanton J.P., Morcet M., Aran C., Graff C., Moreau-LeGolvan Y., and Hebe I. Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems?, Waste Management 26 (2006) 516-525.

[24] Reinhart, Debra R., Faour, Ayman A., You, Huaxin. First-Order Kinetic Gas Generation Model Parameters for Wet Landfills, U.S. Environmental Protection Agency Air Pollution Prevention and Control Division, 2005.

[25] IPCC, 2006.

[26] Ibid.

[27] Personal communication from Sara Hartwell, USEPA, to Andrew Szurgot, March 24, 2008.