Integrated Temperature and Gas Analysis at a Municipal Solid Waste Landfill

James L. Hanson
Lawrence Technological University, Southfield, Michigan, USA

Nazli Yesiller
Wayne State University, Detroit, Michigan, USA

Laurel A. Kendall
Mannik and Smith Group, Dearborn, Michigan, USA

ABSTRACT
This study is conducted to investigate heat and gas production at a municipal solid waste landfill. Periodic temperature and gas measurements have been taken at approximately 140 locations within the waste mass, liner systems, and cover systems at a midwestern U.S.A. landfill since 1999. Increasing temperatures (1 to 15°C/a) were observed for newly placed wastes whereas steady elevated temperatures (50 to 60°C) were observed in older wastes. Liner temperatures increased at a rate of approximately 2 to 4°C/a and stable elevated temperatures in excess of 30°C were observed after 5.5 years and under 42 m of waste height. Anaerobic decomposition and steady landfill gas production commenced within weeks or months of waste placement. Variability of both temperatures and gas levels was observed in wastes due to seasonal climatic fluctuations at shallow depths, whereas relatively stable measurements were obtained at greater depths. The majority of temperature increases for wastes and liners occurs under anaerobic conditions.

1 INTRODUCTION

Landfilling represents the most common form of municipal solid waste (MSW) disposal in many parts of the world. Properly designed waste containment facilities provide environmental protection by effectively separating both waste materials and landfilling byproducts from the surrounding environment. The three common byproducts of landfilling are leachate, gas, and heat. Leachate and gas production have been investigated extensively for compliance with environmental regulations for both byproducts as well as for the alternative energy potential for landfill gas. In contrast, heat generation in landfills has not been commonly investigated or extensively reported. Temperature affects the properties and behavior of all landfill components including wastes and liner materials. In addition, decomposition and degradation of wastes significantly depend on temperature. The interactions between landfill byproducts, in particular temperature interactions, are needed for proper design of landfills. However, these have generally not been well quantified using coupled analyses. This study was conducted to investigate gas and heat production at a MSW landfill.

2 BACKGROUND

In early studies of waste decomposition, initial increases in temperatures resulting in maximum peaks followed by decreases in temperatures were reported following waste placement (as summarized in Rowe, 1998). This trend was attributed to higher heat generation during initial aerobic phase of waste decomposition than later anaerobic decomposition. These trends were not observed in later investigations of landfills, in particular for field conditions. The majority of the currently available data was reported for landfills located in Europe and Japan with less data reported for North American landfills, in particular for U.S. sites (Rowe, 1998; Yesiller and Hanson, 2003).

Field data reported in literature indicate a wide range of temperatures in landfills (Rowe, 1998; Yesiller and Hanson, 2003). Temperatures in excess of 70°C have been reported for wastes and temperatures up to 60°C have been reported at the base of landfills (at liner elevations) in Europe and Japan. Waste temperatures up to 60°C were reported in Canada and U.S. Liner temperatures in the range of 10 to more than 30°C have been reported for liners in North America. The highest temperatures for landfills were generally reported at mid-waste elevations with temperatures decreasing near the top and base of landfills. The temperatures near the top undergo variations similar to seasonal temperature fluctuations, whereas the temperatures at greater depth generally follow stable trends.

Initial decomposition of wastes in a landfill occur under aerobic conditions. Anaerobic conditions prevail upon depletion of oxygen. The two main components of landfill gas generated during the anaerobic phase of decomposition are methane and carbon dioxide (Tchobanoglous et al., 1993). Development of the gases in the anaerobic phase include an early peak of approximately 70% CO_2 and increasing concentations of CH_4. The CO_2 concentrations decrease to approximately 40% and the CH_4 concentrations increase to approximately 60% in the long term. Even though the biochemical reactions of gas production during decomposition and resulting gas concentrations are well documented, the onset and duration of various stages of decomposition have not been extensively reported using field data. Qian et al. (2002) provided a wide range of possible durations for waste decomposition: 3 to 18 months for aerobic conditions and 10 to more than 80 years for total gas generation.

In general, the majority of existing investigations of temperatures do not include a combination of high number of sensors, frequent measurements, and long monitoring periods for a given site. Evolution of temperatures in various components of landfills and comprehensive long term trends have not been fully established. Correlations have not been established between heat and gas production in landfills. This study was conducted to provide such analysis.

3 FIELD TEST SITE

A MSW landfill in Michigan, USA was extensively instrumented to monitor temperatures and gas compositions in each of the following components of the landfill system: bottom liner system (including slopes), waste mass (at various elevations), and cover liner system (Fig. 1). Sensors were placed in longitudinal arrays that terminate at a monitoring station and protrude into a given component of the landfill system. Each sampling location along an array contains both a temperature sensor (Type K thermocouple) and a gas sensing port (custom–built, perforated section tubing with filter housing). Vertical (Type 1, Fig. 1) and horizontal (Types 2, 3, and 4) sensor arrays are used to determine the variations in temperature with depth at a given location and variations in temperature with location at a given depth, respectively. A typical array includes approximately 10 sampling locations. Analysis of data from a total of 142 temperature sensors, 115 gas sensors, and 12 total arrays is included in this paper. The first array was placed at the site in March 1999. Additonal arrays have been installed since then. Data are collected manually using a digital thermometer for weekly temperature surveys and a gas extraction monitor that uses both an infrared sensor and electrochemical cell for determining composition of gas for monthly gas surveys.

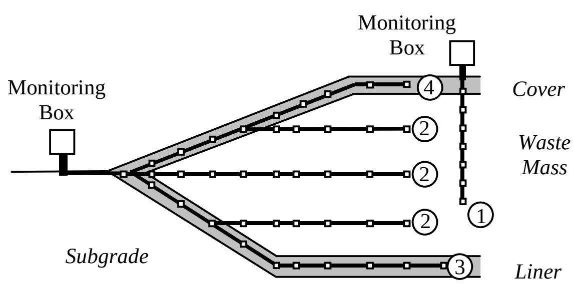

Figure 1. Schematic of temperature and gas monitoring points.

The test site is located in a region that has a humid continental temperate climate. Annual climate statistics include: average daily low temperature = 5.0°C, average daily high temperature = 14.7°C, average extreme low daily temperature = -8.3°C, average extreme high daily temperature = 28.9°C, average annual precipitation = 835 mm, and average snowfall = 1046 mm. The site has a total permitted area of 65 hectares and is subdivided into 11 individual cells. Arrays have been installed in 6 cells at the site. The total amount of waste disposed at the site is approximately 11,450,000 m^3 with an average waste column height of 21 m. Typical waste filling rates range from 1 to 7 vertical m/month. The native subgrade at the site is an illitic clay at 11% moisture content. Bottom liner systems at the site include (from top to bottom): 450-mm-thick protective sand layer, geotextile/geonet composite, 1.5-mm-thick geomembrane, and geosynthetic clay liner. Temporary cover systems consist of lightly compacted clay soils placed directly over wastes at a thicknesses of approximately 600 mm. The average properties of the leachate at the site during the study period were: COD = 2073 mg/l, TOC = 574 mg/l, and pH = 7.68.

4 RESULTS AND DISCUSSION

Temperature variations obtained using horizontal arrays in liners, wastes, and temporary cover systems are provided in Fig. 2. Examples of typical results are provided for various cells. The durations for the reported data are variable in the figure as the instrumentation in the varying cells were placed at different times. Waste placement dates for liners and wastes correspond to approximately time zero in the figure. Temperatures of liners, wastes, and covers vary with seasonal fluctuations near the edges and top of cells (Curves L3, W5, and C1). The fluctuations dampen and steady trends are observed near the centers of cells (remainder of curves). Temperatures stabilize within approximately 20 m of the edges of a cell. Steady elevated temperatures are observed near the center in liners and wastes (Curves L4, W2, W3, and W6). Temperatures increase at an annual rate of approximately 2 to 4°C/a in liners (average rate 2.8°C/a). Temperatures increase at a rate of approximately 1 to 15°C/a in wastes (average rate 7°C/a). Somewhat higher intitial increases were observed for wastes that were placed during warm seasons (Curves W2, W3, and W4), whereas lower initial increases were observed for wastes placed during cold seasons (Curves W1, W6, and W7). Similar seasonal trends were observed for liner temperatures, Curve L4 for warm season vs. Curves L1 and L2 for cold season. An initial rapid increase in liner temperature was observed over a short period subsequent to waste placement during extreme cold seasons (Curves L1 and L2); however, this was not a lasting trend and may be attributed to temperature of waste being placed, insulating effects, and overall seasonal warming rather than optimal decomposition. While the overall long-term temperature increase is similar for waste placement both in warm and cold seasons, the magnitude of temperatures attained are higher for wastes placed during warm seasons than during cold seasons.

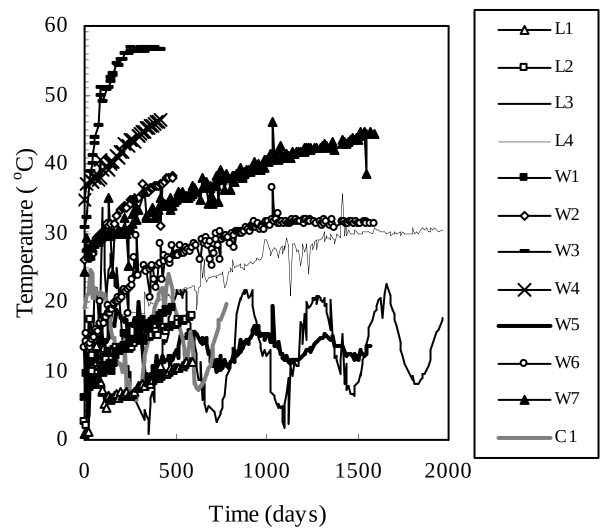

Figure 2. Temperature vs. time plots for horizontal arrays.

Rates of temperature rise were analyzed as a function of nature of wastes. A cell that received fresh waste had average temperature increase rates of approximately 10°C/a whereas a cell that received large fractions of old waste (approximately 25 years old) had temperature increase rates of approximately 2.5°C/a. The difference in temperature increase rates was attributed to age of waste as the two cells were filled using similar rates during winter seasons (in different years). Similar effects of age of waste were observed for liner temperatures. For similar cold-season filling (in different years), the rates of temperature increase in two liner systems were approximately 4°C/a and 2°C/a for placement of fresh waste and predominantly 25-year old waste, respectively.

Elevated stable temperatures were observed towards the central region of a cell whereas lower stabilized temperatures were observed at intermediate zones between the central region and the edges. The time required to reach stabilized temperatures varied as a function of location. Seasonal temperature fluctuations remain towards the edges (Curve W5), stabilized temperatures are reached after approximately 250 to 1000 days for intermediate zones (Curves W3 and W6) and longer periods (in excess of 1400 days) for the central region (Curves L4 and W7).

Within vertical arrays, waste temperatures fluctuated with seasonal variations near the surface, whereas steady elevated temperatures were obtained at depth (Fig. 3). Seasonal variations at shallow depths (Curve S1 for 1 m depth) dampened within approximately 8 m depth of waste. In general, higher temperatures were measured at greater depths and in older wastes up to certain limits. Temperatures of wastes at great depth (approaching bottom liner elevations) were lower than peak values measured towards the center of a waste mass. Temperatures for wastes with ages greater than approximately 10 years had lower temperatures than peak values measured for wastes with ages between 5 and 7 years. A comparision of temperatures along a single vertical array demonstrates the influence of depth. Waste at 13 m depth (Curve M3) stabilized at approximately 47°C, waste at 23 m depth (Curve M1) is approaching stabilized temperatures of approximately 56°C, whereas waste at 27 m depth is still increasing slightly, but at approximately 52°C (Curve D2). A comparison of stabilized temperatures at consistent depth (13 m) in 3 different cells demonstrates the influence of age of waste. Temperatures at 13 m depth were approximately 47°C in 4-year old waste (Curve M3), 56°C in 7-year old waste (Curve M2), and 47°C in 13-year old waste (Curve M4). Maximum stable temperatures measured in the waste mass at the site were 56°C, obtained for 3 cells with ages 5 to 7 years old, at depths ranging from 13 to 26 m. The maximum temperatures occured at locations near the mid-depth of the cells. Maximum stable temperatures measured in liners were 30°C for liners below 5.5-year old wastes at a depth of 42 m.

Typical trends for onset of gas and heat production upon waste placement are presented in Fig. 4 for wastes. Gas production trends observed in wastes include a peak of CO_2 concentration followed by a decrease to a steady value of approximately 40%; a gradual increase in CH_4 concentration to approximately 60%; and a rapid depletion of O_2 concentration. For sensors in the waste, the time for depletion of oxygen was approximately 14 to 70 days, time for peak of carbon dioxide was approximately 28 to 90 days, and time for stabilization of peak methane production was approximately 130 to 190 days (resulting in approximately 10.5% increase in methane concentration per month). In general, the steady production of CH_4 occurs under continually increasing temperatures or steady elevated temperatures depending on age of waste. The continually increasing temperature trends during this period indicate that significant heat is produced during the anaearobic phase. In most cases, the temperature rise is linear and is not affected by the transitions of gas composition. Landfill gas production was observed to commence below relatively low waste heights (prior to final waste heights).

Landfill gas is also observed in the liner system with similar compositions and trends (Fig. 5). However, the transition from air to anaerobic conditions takes longer in liners than in the waste mass. For liners: average time for depletion of oxygen was approximately 80 to 190 days, time for peak of carbon dioxide was approximately 120 to 150 days, and time for stabilization of peak methane production was approximately 310 to 400 days (resulting in approximately 6.5% increase in methane concentration per month). Similar to measurements in the waste mass, the correlations between heat and gas production indicate that the majority of temperature increase occured during anaerobic phase of decomposition in liner systems. Periods required for stabilization of elevated temperatures were significantly greater than for stabilization of peak gas production. Similar to heat production trends, gas production varied in different cells at the site. Placement of fresh wastes resulted in earlier onset of peak gas production than placement of older wastes. Higher rates of increase in methane concentration were measured for the waste mass (in comparison to liners) and for waste placement in warm seasons (in comparison to cold seasons).

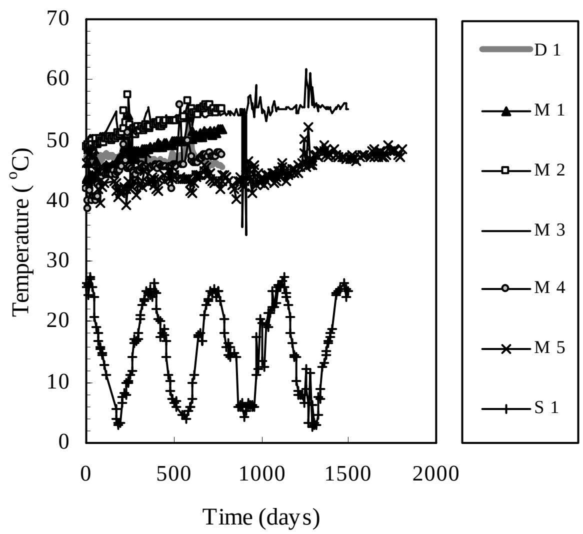

Figure 3. Temperature vs. time for vertical arrays.

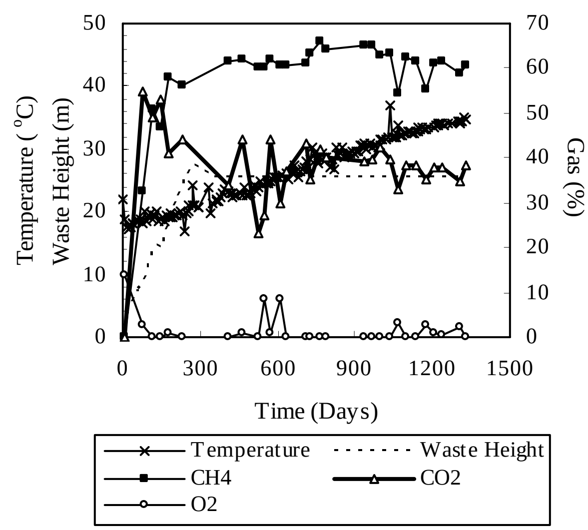

Figure 4. Gas and temperatures for waste.

Variation of CH_4 and CO_2 concentrations follows seasonal fluctuations similar to temperatures at relatively shallow depths (Fig. 6). A phase lag is observed in the variation of gas concentrations in comparison to the variation of temperatures. Seasonal variations at shallow depths dampen within approximately 5 m depth of waste. The curves in Fig. 7 represent the upper and lower bounds for all temperature and methane measurements at given depths for a vertical arrray in the waste mass. The variability of both temperatures and methane concentrations are greater at the surface than at depth

(Fig. 7). Overall, a decrease in variability and an increase in magnitude is observed with depth for both temperatures and methane concentrations.

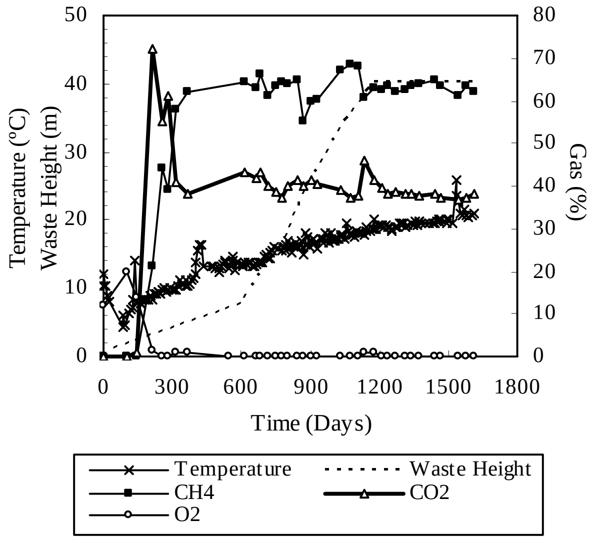

Figure 5. Gas composition and temperature for liner.

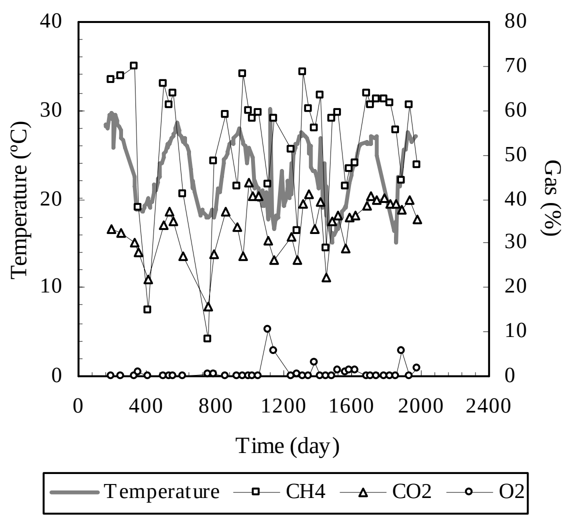

Figure 6. Seasonal fluctuation of temperature and gas in wastes.

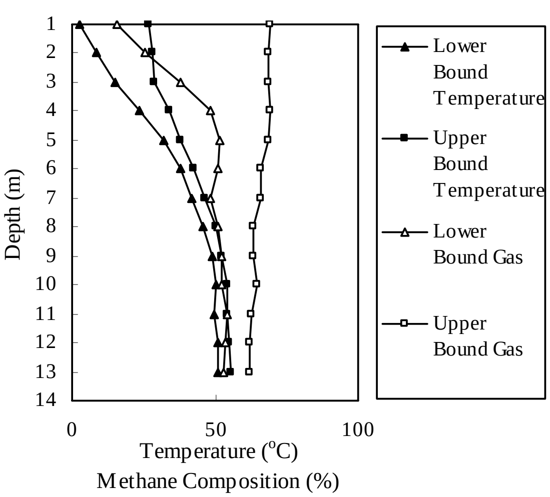

Figure 7. Envelopes for temperature and gas concentration with depth.

5 CONCLUSIONS

The conclusions provided below are drawn based on long-term monitoring of temperatures and gas compositions within various components of a municipal solid waste landfill:

1. Waste temperatures and gas concentrations followed seasonal fluctuations near the edges and surface whereas stabilized trends occured near central locations and at depth. Temperatures and methane concentrations stabilize within approximately 20 m of the edges of a cell. Stable temperatures up to 56°C and stable methane concentrations of approximately 60% were observed at depths greater than approximately 8 m.
2. Liner temperatures and gas concentrations follow seasonal fluctuations near the edges whereas stabilized trends occur towards the central regions of the liner systems. Stable methane concentrations of approximately 60% and stable temperatures up to 30°C were observed at distances greater than approximately 20 m from the perimeter of a cell.
3. Transition from aerobic to anaerobic conditions (taken as onset of peak methane production) occurs over approximately 160 days for wastes and 360 days for liners. The majority of temperature increase occurs under anaerobic conditions.
4. Rates of temperature increase of approximately 1 to 15°C/a were observed in waste masses upon initial waste placement. Lower rates were observed for placement of older wastes. Rates of temperature increase of approximately 2°C/a and 4°C/a were observed in liners upon placement of old and new wastes, respectively.
5. Maximum stable temperatures of approximately 56°C were obtained in 5- to 7-year old wastes at mid-depths of the landfill between approximately 13 to 26 m. Both younger and older wastes had lower stabilized temperatures than these peak values. In addition, both shallower and deeper wastes (approaching liner elevations) had lower stabilized temperatures than these peak values.
6. Overall, variability of both temperatures and methane concentrations were greater near the surface than at depth, where relatively stable, elevated conditions prevail.

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