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Heat Extraction from Municipal Solid Waste Landfills

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ABSTRACT

Municipal solid waste in landfills has been shown to reach temperatures of greater than 50 °C for more than 20 years due to the activity of methanotrophic bacteria. Other landfills with industrial or mining wastes may reach even greater temperatures. The internal heat generation in landfills provides an interesting renewable heat source that can be exploited for direct heating of nearby buildings or infrastructure or for augmenting industrial processes. This paper uses measurements from a monitored geothermal heat extraction system installed in a landfill cell in Santee, CA to estimate the ranges of geothermal energy available for extraction over the lifetime of the landfill.

1. INTRODUCTION

Municipal solid waste (MSW) is generated in nearly every community in the United States, and the most common form of waste management is long-term storage within a closed landfill. Biodegradation of MSW under the moist, mesophilic, and anaerobic conditions generally presented within closed landfills leads to the generation of biogas (predominantly methane) and heat, increases in waste temperature, consumption of the biomass component of the MSW, and settlement of the landfill settlement (Nocko et al. 2018). The heat generated from the biodegradation process is a renewable energy resource that can be extracted from the waste mass and used as a renewable energy source for direct heating of nearby facilities or for augmenting industrial processes. Such extraction of heat may also affect the landfill operator's ability to regulate the internal temperature regime within the landfill. The strategic extraction of heat can be used for several applications, such as changing the methane generation rate within the waste, which is sensitive to the temperature, or to reduce the temperature gradient across the landfill base liner in order to minimize the potential for clay liner desiccation (Coccia et al. 2013) or protection of liner geosynthetics (Jafari et al. 2014a). Although geothermal heat extraction systems may be best suited to MSW landfills as the expected temperature range of 40 to 65 °C and the duration of heat availability are well understood (Yesiller et al. 2005; Hanson et al. 2008, 2010, 2013), this approach may also be applicable to the control of elevated temperature landfills (i.e., exceeding 65 °C) that contain specialized waste such as construction demolition debris, industrial and mining waste, and sanitary dumps (e.g., Jafari et al. 2014b). The elevated temperatures in these landfills are typically generated by exothermic chemical reactions, spontaneous combustion, and smoldering/pyrolysis combustion, and specialized heat exchangers may be required.

This paper presents monitoring data from an instrumented MSW landfill cell in order to estimate the range of thermal energy that is available for extraction as a function of time after the closure of the landfill. Two models are used, including a model proposed by Young (1992) and later applied by Yesiller et al. (2005) that is based on the stoichiometry of the chemical equation for transformation of glucose into CO_2 and CH_4, and a model developed by Hanson et al. (2008) that uses climatic and operational variables to estimate the amount of heat generated.

2. INSTRUMENTED LANDFILL

To better understand the development of stable mesophilic temperatures within a MSW landfill and to monitor temperature changes in the waste during operation of the geothermal heat extraction system, 24 temperature sensors on thermistor strings (i.e., a cable that houses several thermistors at different locations along its length) were installed in a newly-constructed landfill cell at the Sycamore landfill in Santee, CA. As this is a preliminary investigation of this technology, the geothermal heat extraction system and monitoring system only covered a small area of the waste cell, as shown in Figure 1. The sensors were placed at three different levels during placement of waste, including one at the base liner, one 6 m above the base liner, and one 12 m above the base liner (Figure 2). Three additional lifts of waste with a total height of 18 m were placed above the upper instrumentation level for a total MSW height of 30 m in the cell. The layout of the three levels of heat exchangers and thermistors is shown in Figure 2. The side slope was protected with an organic daily cover material.

Geothermal heat exchanger pipes were installed in each waste lift, with a typical picture of the heat exchanger system shown in Figure 3. The high-density polyethylene (HDPE) pipes having an inside diameter of 25 mm were connected in a closed-loop manner as shown in Figure 3, such that heat will be extracted from the waste by circulating fluid from an industrial chiller unit through the pipe loops. Once the development of temperature profiles within the waste have been characterized absent of any heat extraction the heat exchangers will be used in a future study to investigate the thermal properties of the waste and the range of heat fluxes that can be used to assess the heat extraction properties of MSW. After the pipes for a given layer were placed, they were pressurized with water to 300 kPa and covered with a layer of soil for protection purposes. After placement of the waste atop the geothermal heat exchangers was completed, the pressure was found to be still present in the pipes, confirming that no leaks occurred. Further, water was circulated through the pipes to ensure that no kinking or compression of the pipes occurred. The thermistor strings were then connected to a datalogger, and the heat exchanger pipes were insulated and connected to a manifold at the toe of the slope as shown in Figure 4.

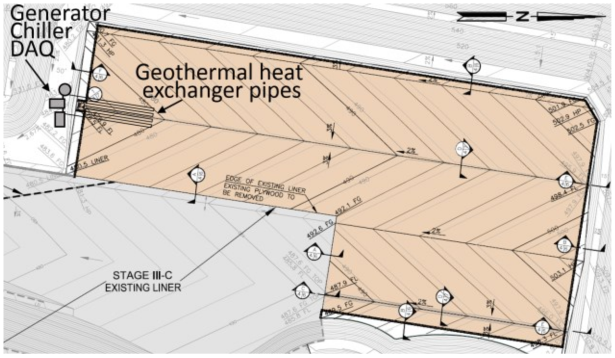


Figure 1. Plan view of the landfill cell showing the locations of the geothermal heat exchanger system

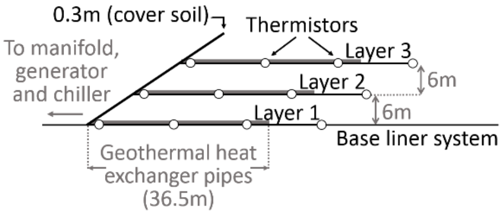


Figure 2. Cross-section showing thermistor strings within the landfill.

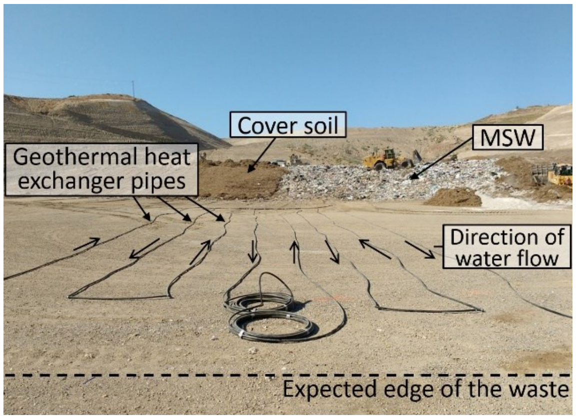


Figure 3. Placement of heat exchanger system at the bottom of the landfill cell, with waste placement progressing from the North of the cell toward the heat exchangers

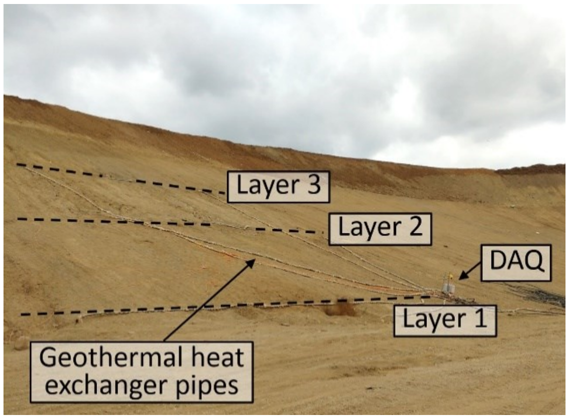


Figure 4. Slope of the waste cell after the placement of all layers of the system and insulation of the pipes.

Waste temperatures were measured at the three different levels over a 13-month period following the placement of the waste. An example of the variations in temperature with time for the sensors placed at the middle level of the landfill along with the ambient air temperature are shown in Figure 5. The temperature of the waste is clearly different from the ambient air temperature, although the sensor that was 1.5 m from the face of the landfill cell was affected by the outside air temperature because of some erosion of the daily cover overlying the waste during strong rains in the winter months. The temperature within the body of the waste approaches a temperature of approximately 50 °C. The fact that waste temperatures reached relatively high values in less than a year shows not only the potential for heat extraction but also that this extraction can start in a relative short time period after the installation of the system during waste placement. Research by Yesiller et al. (2005) and Hanson et al. (2005) indicates that these elevated temperatures for more than 20 years will be sustained in the waste both due to continued biodegradation and due to the low thermal conductivity of the waste that limits the loss of heat from the sides of the landfill cell. This indicates that MSW landfills are a long-term thermal energy resource. Future experiments involving circulation of cold fluid through the heat exchangers are planned to provide an understanding of their heat exchange characteristics which will help the practical implementation of this technology. These will be reported in the next phase of work.

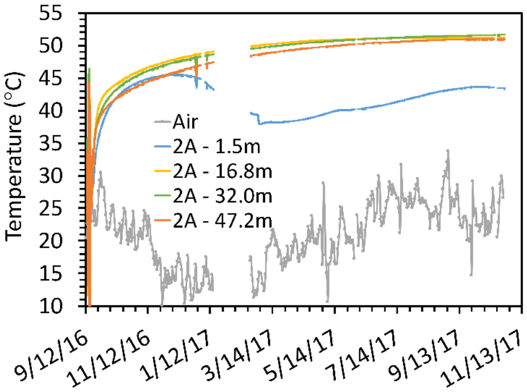


Figure 5. Waste temperatures at different distances from the slope face at a height of 6 m above the base liner.

The heat content analysis of Yesiller et al. (2005) was used to estimate the heat gain due to biodegradation. First, the unheated baseline waste temperatures as a function of time t and depth x were determined using the analytical solution to the heat conduction equation proposed by ORNL (1981):

$$T_{(x,t)} = T_m - A_s \cdot e^{-x\sqrt{\pi/365\alpha}} \cdot cos\left[\frac{2\pi}{365}\left(t - t_0 - \frac{x}{2}\sqrt{\frac{365}{\pi\alpha}}\right)\right] \qquad (1)$$

where T_m is the mean annual earth temperature, t_0 is a phase constant, A_s is the amplitude of a surface temperature wave, and α is the thermal diffusivity of the waste. The waste was assumed to be homogeneous and α was assumed to be 4.3×10^{-2} m^2/day (Yesiller et al. 2005; Hanson et al. 2013). The heat content (HC) was calculated as the area between the curves of measured and estimated unheated temperatures divided by the duration of the analysis (Yesiller et al. 2005), as shown in Figure 6. The heat content representing the total energy available above the initial temperature of the waste is 27.7 °C/day/day. In some cases, it may not be desirable to reduce the temperature of the waste below 35 °C as it may slow the biodegradation process (Farquhar and Rovers 1973). However, it is still expected that heat will be generated if the temperature is reduced below 35 °C, and that the transient heat extraction process can be optimized to ensure that there is sufficient heat available for a given application.

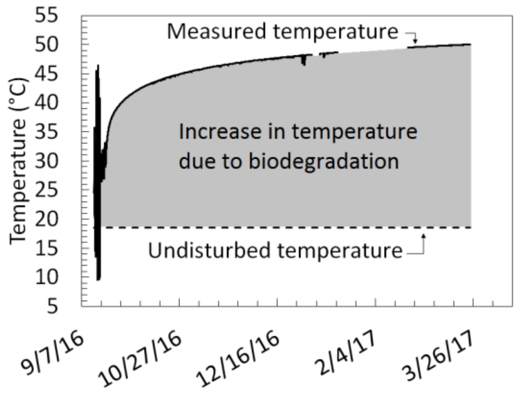


Figure 6. Approach to calculate the heat content of the waste.

3. HEAT GENERATION MODELS

To estimate the amount of thermal energy available in the MSW for extraction, the models of Young (1992) and Hanson et al. (2008) were evaluated for the conditions representative of the Sycamore landfill. While the model of Young (1992) uses the heat capacity of MSW and the variation in temperature observed to estimate the heat available, the model of Hanson et al. (2008) estimates the total heat generated within the waste based on climatic and operational condition factors. The model of Hanson et al. (2008) also considers the heat generated during the entire process of biodegradation (more than 20 years), while the model of Young (1992) focuses on the period where the temperature is at a peak value.

In the model of Young (1992), the heat generated is obtained based on the stoichiometry of the chemical reaction for transformation of glucose into CH_4 and CO_2 (landfill gases), which also releases heat as a side effect. Only a fraction of the total energy E_{TOT} liberated from this process is used for heating the waste, while the rest of the energy is used to evaporate water and is lost to the surroundings. The energy $E_{\Delta T}$ used to heat the MSW is calculated as:

$$E_{\Delta T} = E_{TOT}.M(T) = \Delta T.C \qquad (2)$$

where ΔT is the variation in temperature of the MSW, C is the volumetric heat capacity of the MSW (MJ/m^3K) and M(T) is the fraction of the total energy used to heat the waste. M(T) is a function of temperature and its values are defined by Young (1992) using a curve that can be used for all types of waste. The volumetric heat capacity of the MSW was assumed to be 2.1 MJ/m^3K and the ΔT was the difference between the peak temperature of the waste (52 °C) obtained from Figure 5 and the undisturbed temperature calculated by ORNL (1981) model in Equation (1). Assuming that all the energy used to heat the MSW can be withdrawn as heat, the MSW in Sycamore landfill would have 70 MJ/m^3 available for extraction based on this model.

As an alternative, Hanson et al. (2008) developed an empirical exponential growth and decay function to model the heat generation rate in landfills as a function of time, given as follows:

$$H = A\left[\frac{Bt}{B^2 + 2Bt + t^2}\right]e^{-\sqrt{\frac{t}{D}}} \qquad (3)$$

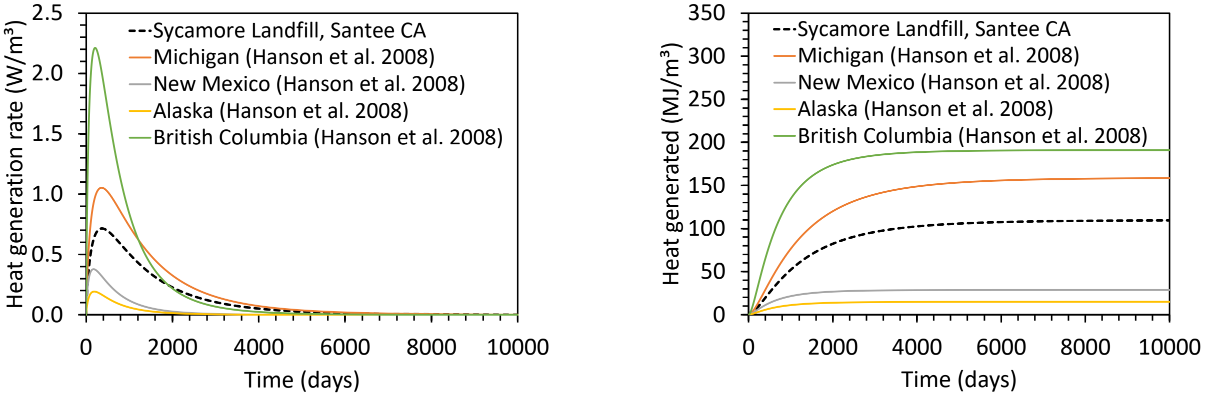
where H = heat generation rate (W/m^3), t = time (days), A = peak heat generation rate factor (W/m^3), B = shape factor (days), D = decay rate factor (days). The values of A, B, and D are defined using the following expressions:

$$A = -7.92 + 0.12\lambda \qquad (4)$$

$$B = -2027 + 20.47\lambda - 0.015\lambda^2 \qquad (5)$$

$$D = 55.5 + 2.79F \qquad (6)$$

where λ is the climatic-operation condition factor that can be calculated as the product of the average daily air temperature and the average annual precipitation divided by the compacted unit weight of the waste, and F is the operational condition factor defined as the vertical waste filling rate in m/year. The results from the model of Hanson et al. (2008) are shown in Figure 7(a) and 7(b). The model indicates that 109 MJ/m^3 will be generated in the MSW after reaching steady-state conditions. However, it should be noted that the model of Hanson et al. (2008) accounts for all the heat generated by the waste, but it doesn’t specify the fraction of it that is used to increase the temperature of the MSW and that is lost due to evaporation of water. Therefore, the amount of heat estimated using the model of Hanson et al. (2008) method is higher than the amount of heat estimated using the model of Young (1992).



(a) (b)

Figure 7. Results of the model of Hanson et al. (2008) for the Sycamore landfill along with those from other landfills in North America: (a) Heat generation rate over time; (b) Cumulative heat generated over time

The quantifications of thermal energy available per cubic meter can be evaluated for the cell that is currently under construction at the landfill shown in Figure 1. The approximate area of this stage is 33,098 m^2 with a total of height of approximately 30.5 m. Neglecting the slope of the cell (assuming a box of waste), the total volume of waste in this cell is 1,009,489 m^3. Accordingly, for the steady-state heat generated of 109 MJ/m^3 at the Sycamore landfill according the model of Hanson et al. (2008), the total energy available in the landfill is 110,034 GJ. However, using the model of Young (1992) that accounts for the energy lost due to evaporation of water, the total energy available in the landfill would be 70,664 GJ. As there are several other similar-sized cells at the landfill, these quantities of thermal energy represent a large amount of localized thermal energy that can be exploited for practical purposes.

4. CONCLUSIONS

The temperature monitoring results from a municipal solid waste landfill in Santee, CA were used to estimate the range of geothermal energy available for extraction. Due to the large volume of waste at the landfill under investigation, an appreciable amount of geothermal energy is available for extraction. This heat may be regenerated after extraction due to additional biodegradation of the waste. Municipal solid was landfills represent a long-term sustainable strategy to recover energy from our waste stream beyond methane capture. This strategy is particularly important for countries like the United States who choose to encapsulate their waste in a landfill setting with the goal of protecting the environment, as this poses a very expensive waste management strategy whose costs may be offset through energy recovery.

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