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Heat management strategies for MSW landfills

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ABSTRACT

Heat is a primary byproduct of landfilling of municipal solid waste. Long-term elevated temperatures have been reported for MSW landfills under different operational conditions and climatic regions around the world. A conceptual framework is presented for management of the heat generated in MSW landfills. Three main strategies are outlined: extraction, regulation, and supplementation. Heat extraction allows for beneficial use of the excess landfill heat as an alternative energy source. Two approaches are provided for the extraction strategy: extracting all of the excess heat above baseline equilibrium conditions in a landfill and extracting only a part of the excess heat above equilibrium conditions to obtain target optimum waste temperatures for maximum gas generation. Heat regulation allows for controlling the waste temperatures to achieve uniform distribution at target levels at a landfill facility. Two approaches are provided for the regulation strategy: redistributing the excess heat across a landfill to obtain uniform target optimum waste temperatures for maximum gas generation and redistributing the excess heat across a landfill to obtain specific target temperatures. Heat supplementation allows for controlling heat generation using external thermal energy sources to achieve target waste temperatures. Two approaches are provided for the supplementation strategy: adding heat to the waste mass using an external energy source to increase waste temperatures and cooling the waste mass using an external energy source to decrease waste temperatures. For all strategies, available landfill heat energy is determined based on the difference between the waste temperatures and the target temperatures. Example analyses using data from landfill facilities with relatively low and high heat generation indicated thermal energy in the range of −48.4 to 72.4 MJ/m^3 available for heat management. Further modeling and experimental analyses are needed to verify the effectiveness and feasibility of design, installation, and operation of heat management systems in MSW landfills.

1. Introduction

Significant amounts of heat are generated in different types of waste containment facilities including municipal solid waste (MSW) landfills. Landfills that are used solely to contain municipal solid waste incinerator ash and mining waste piles (Yeşiller et al., 2015a). Heat generation occurs due to bacterially mediated decomposition of the organic fraction of the waste materials and also due to chemical and biochemical reactions that occur within the wastes. Heat is a primary byproduct of landfilling of municipal solid waste in addition to landfill gas and leachate.

An extensive review of heat generation in MSW landfills and other types of containment facilities was provided in Yeşiller et al. (2015a). In MSW landfills, waste temperatures tend to increase over a period of months to years until reaching steady elevated temperature conditions (as compared to ambient ground temperatures) generally at the central regions of the waste mass. Cyclic effects of seasonal temperature fluctuations typically are present at shallow depths near the surface and at locations near the perimeter of the waste mass. Long-term elevated temperatures have been reported for MSW landfills (Yeşiller et al., 2005; Hanson et al., 2010). Temperatures up to 60–90 °C were measured in typical solid waste landfills located in different climatic regions across the world (Yeşiller et al., 2015a). Temperatures over 100 °C were reported in gas wellheads at a landfill containing significant amounts of aluminum processing waste located in a cold climate (Jafari et al., 2014).

Waste decomposition and resulting gas and heat generation are coupled processes. In general, decomposition of the organic constituents within wastes is enhanced with increasing temperatures. Such enhanced processes continue up to limiting temperatures. Waste decomposition and landfill gas generation have long been

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studied. In laboratory experiments, optimum temperature ranges for the growth of bacteria responsible for decomposition of organic constituents in MSW were determined to be: 35–40 °C for mesophilic bacteria and 50–60 °C for thermophilic bacteria (Tchobanoglous et al., 1993; Cecchi et al., 1993). Maximum gas production from waste decomposition was identified to occur at temperature ranges between 34 and 41 °C based on laboratory investigations (DeWalle et al., 1978; Hartz et al., 1982; Mata-Alvarez and Martinez-Viturtia, 1986) and a temperature range of 40–45 °C was identified as the optimum range for gas production at a landfill located in a temperate climate (Rees, 1980a,b). Highly reduced and delayed gas generation was observed at facilities with low waste temperatures based on analysis conducted and data obtained at landfills located in North America (Hanson et al., 2006; Yesiller et al., 2015a).

This investigation was conducted to develop strategies for management of heat generation and elevated temperatures in landfill systems. Landfilling currently is and in the future expected to continue to be, the main means used for management of municipal solid waste in the U.S. as well as various other countries. Opportunities exist for beneficial use of the heat generated in MSW landfills as an alternative energy source as well as better use of the heat generated within the landfills for optimum operation of the landfill systems. Strategies developed for landfill heat management are presented herein. A heat extraction strategy originally proposed in Yesiller et al. (2015b) is further developed and additional strategies are included. Available heat energy in landfill facilities is assessed and example data and analysis are provided for landfills with relatively low and high heat generation.

2. Heat management strategies

For management of landfill heat energy and elevated temperatures at municipal solid waste landfills, multiple conceptual scenarios are possible to form a framework. Three main strategies are outlined herein for the management of heat: extraction, regulation, and supplementation.

2.1. Heat extraction

Heat extraction allows for beneficial use of the excess landfill heat as an alternative energy source (Yesiller et al., 2015b). For the heat extraction strategy, two approaches are developed with different potential implications for management of landfills.

- E1: Extracting all of the excess heat above baseline equilibrium conditions in a landfill system. In this approach, heat extraction results in waste temperatures consistent with unheated waste temperature, $T_{(x,t)}$. The $T_{(x,t)}$ represents stable waste temperatures at a given depth (x) and time (t) under conditions of no heat generation. The baseline equilibrium temperatures are controlled by specific waste properties and the specific climatic region.
- E2: Extracting only a part of the excess heat to obtain target optimum waste temperatures for maximum landfill gas generation. In this approach, heat extraction results in waste temperatures consistent with the temperature range for optimal landfill gas generation, T_{LFG}, which has been reported to range from approximately 35–45 °C.

The difference between the elevated landfill temperatures (T_{waste}) and the lower temperature target (either $T_{(x,t)}$ or T_{LFG}) is quantified as cumulative temperature differential, ΔT. The ΔT represents the temperature change that a unit volume of the waste mass will be subjected to due to heat extraction. The ΔT is determined using three steps: (*i*) waste temperature (T_{waste}) versus time data are plotted; (*ii*) the target temperature, either $T_{(x,t)}$ or T_{LFG}, (based on approach used, E1 or E2) is superimposed on the plot; and (*iii*) the area between the two temperature histories is calculated as presented in Fig. 1. Positive values of ΔT indicate that waste temperatures are overall greater than the target temperature. The target temperature, T_{LFG}, is a constant temperature, which does not change with depth or time. The baseline unheated temperature, $T_{(x,t)}$, is the temperature of the waste under the influence of only seasonal subsurface temperature fluctuations (and not including any heat generation). $T_{(x,t)}$ can be calculated using conventional near-surface earth temperature theory (ORNL, 1981) by adopting appropriate physical and thermal properties for MSW (e.g., Yesiller et al., 2015a). Next, a time-averaged temperature differential, ΔT_{avg}, is calculated to normalize the cumulative temperature differential, ΔT, for temporal fluctuations of temperatures (waste temperatures and/or target temperatures). The ΔT_{avg} is determined by dividing the calculated area, ΔT (units of °C-day), (Fig. 1) by the total period of observation (Hanson et al., 2010; Yesiller et al., 2015a). The resulting ΔT_{avg} has units of °C-day/day. To avoid seasonal bias, time periods representing full annual cycle(s) are used. The average temperature differential is designated as $\Delta T_{avg\text{-}(x,t)}$ when the target temperature in the heat extraction application is $T_{(x,t)}$ (E1) and as $\Delta T_{avg\text{-}LFG}$ when T_{LFG} (E2) is the target temperature for heat extraction. The ΔT_{avg} calculations are repeated along the depth of a waste mass using available measured waste temperatures.

Thermal properties required to determine baseline unheated waste temperatures and heat energy of the wastes include heat capacity and thermal diffusivity. Heat capacity is determined by summing volumetric heat capacity (MJ/m^3 K) of individual constituent components (using standard values, e.g., CRC (2012)) of the waste on a volumetric basis (using appropriate waste composition, e.g., USEPA (2016)). Thermal diffusivity (m^2/s) is determined using a combination of: (a) analytical approaches, (b) probe methods (Hanson et al., 2000), and (c) surface trends using ground surface temperature theory together with measured temperature envelopes (Yesiller et al., 2008). Details regarding determination of thermal properties are provided in Hanson et al. (2000, 2008, 2013) and Yesiller et al. (2008).

The thermal energy of a unit volume of waste is determined using the average temperature differential and heat capacity of the waste. The heat energy of the unit volume of waste located at the depth of interest is determined by multiplying the ΔT_{avg}

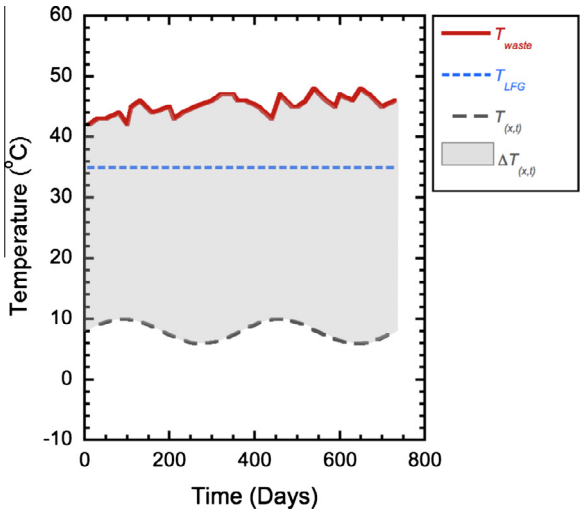

Fig. 1. Determination of temperature differential.

with the volumetric heat capacity of the waste. The resulting heat energy, designated E_h, describes heat gain of the unit volume from the onset of waste placement up to the last date used for calculating the E_h and is reported in units of MJ/m^3. E_h accounts for accumulation of heat over time and represents in-situ heat energy available for heat management. This energy calculation methodology can be extended to the entire waste mass, by summing the unit volume of heat energy values determined incrementally with depth over the entire height and lateral extent of a waste mass to establish cumulative available heat energy, E_H. Total heat energy (E_{total}) can be estimated by adding thermal losses in the landfill system to E_H. Thermal losses are determined using conductive heat transfer analysis (Yesiller et al., 2015a) and therefore are time dependent in magnitude. The energy calculated using this approach represents the net accumulated heat energy in relation to a given threshold temperature (e.g., $T_{(x,t)}$, T_{LFG}). If the energy is extracted or regulated, heat generation will continue in the waste mass with time (at a potentially modified rate). Therefore, both E_h and E_H provide conservative estimates for thermal energy available for management.

2.2. Heat regulation

Heat regulation allows for controlling and manipulating heat generation to achieve target waste temperatures by redistributing the heat generated in a landfill with no active external heat transfer. For the heat regulation strategy, two approaches are developed with different potential implications for management of landfills.

- R1: Redistributing the excess heat across a landfill facility to obtain uniform target optimum waste temperatures (T_{LFG}) for maximum gas generation. In this approach, excess heat generated in certain regions of the landfill (locations where $T_{waste} > T_{LFG}$) is transferred to other regions with low heat energy (locations where $T_{waste} < T_{LFG}$). The resulting uniform waste temperature at or near T_{LFG} promotes optimum landfill gas generation throughout the landfill.
- R2: Redistributing the excess heat across a landfill to obtain specific uniform target temperatures (T_{cons}). In this approach, heat is transferred between locations where the $T_{waste} \neq T_{cons}$. The waste temperatures, T_{waste}, can be higher or lower than the constant target temperature, T_{cons}. When $T_{waste} > T_{cons}$, the excess heat is transferred to other regions with low heat generation and when $T_{waste} < T_{cons}$, the heat deficit is offset with heat transferred from regions with high heat energy. The resulting T_{cons} is used to regulate the temperature to control the rate of chemical and biochemical reactions, delay decomposition and gas generation, accelerate or decelerate settlement, or for other considerations in management of a landfill facility.

The heat energy available for transfer and redistribution in the heat regulation strategy is calculated using the general methodology provided in Section 2.1 (Fig. 1). Measured waste temperatures and waste thermal properties are used to determine the excess heat energy available for redistribution at a given facility.

2.3. Thermal supplementation

Thermal supplementation allows for controlling and manipulating heat generation to achieve target waste temperatures by adding heat to or removing heat from the landfill using external thermal energy sources. Extra energy is required in this case, which may be offset by the benefits resulting from the use of the supplementation strategy. For the heat supplementation strategy, two approaches are developed with different potential implications for management of landfills.

- S1: Supplementing heat generation at a landfill for heating the landfill system using an external energy source (active heating). In this approach, heat supplementation results in landfill system temperatures above levels occurring due to biochemical processes and above levels that can be obtained with only redistribution of existing heat in the system.
- S2: Supplementing heat generation at a landfill for cooling the landfill system using an external energy source (active cooling). In this approach, heat supplementation results in landfill system temperatures below levels that can be obtained with only heat extraction, redistribution of existing heat in the system, and/or interactions with the ambient ground temperatures.

The thermal energy (heating or cooling) required in the supplementation approaches is calculated using the general methodology provided in Section 2.1 (Fig. 1). Measured waste temperatures, waste thermal properties, and target temperature(s) are used to determine the excess heat energy required at a given facility. The thermal regime of the landfill is manipulated using the supplementation strategy to control the rate of waste temperature change occurring in a landfill, control the rates of chemical and biochemical reactions, delay or accelerate decomposition and gas generation, accelerate or arrest settlement, or for other considerations in management of a landfill facility.

2.4. Heat extraction, regulation, and supplementation systems

The placement and operation of heat management systems are directly influenced by the specific thermal regime of the waste mass at a given site. Based on extensive data and analysis from landfills located in different climatic regions in North America (Yesiller et al., 2005, 2015a; Hanson et al., 2006, 2010), the authors have identified two common thermal regimes in MSW landfills. In colder and wetter climates, a high temperature central core of waste is present with surrounding lower temperatures near the surface, base, and sides of a landfill, whereas in warmer and drier climates, an extended high temperature zone is present from central core through the base of the waste mass (Fig. 2). The temperatures along the top boundaries of the landfills are influenced by cyclic seasonal air temperature fluctuations and the side and bottom boundary temperatures are influenced by the local mean annual earth temperatures. Access to and use of the heat from central zones of the waste mass is critical for both extraction and

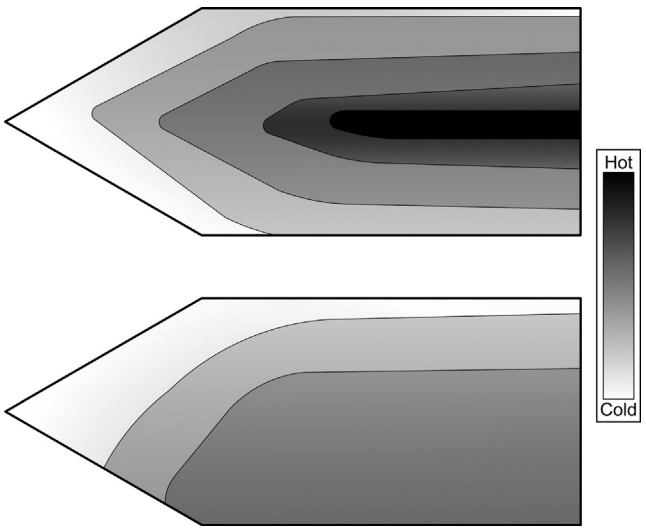

Fig. 2. Typical MSW landfill thermal regimes.

regulation strategies in cold and wet climates. Less heat redistribution due to regulation would occur for the applications in warm and dry climates (Fig. 2).

A schematic is presented in Fig. 3 that shows the possible heat management systems that can be installed within a waste mass at a MSW landfill. Both horizontal and vertical systems can be used for extraction, regulation, and supplementation strategies. Horizontal systems can be used to extract/remove heat from or add heat to specific depths over large areal extent. A single horizontal system or multiple horizontal systems can be placed along the central core of a landfill with high or low heat generation to extract heat above $T_{(x,t)}$ or T_{LFG} for operation in line with heat management strategy E1 or E2, respectively; and also to add or remove heat in line with strategies S1 and S2, respectively. The horizontal systems also can be used to redistribute heat along a specific depth in a landfill, in particular from central heated zone to locations near the sides/perimeter edges of a waste mass. Vertical systems can be installed along depth profiles to transfer and redistribute heat along the length of the system, in particular from central heated zone to depths near the top and bottom of the waste mass (in line with strategies R1 or R2). The vertical systems also can be used to extract heat from all depths along the profile of the system or to add/remove heat to/from all depths along the profile of the system.

High levels of internal heat transfer (within the landfill) are expected to occur for vertical installations. Vertical systems allow for temperatures to equilibrate throughout the depth of the waste mass taking advantage of the high thermal gradients that develop with depth. Horizontal systems allow for reaching the hottest zones of the landfill over maximum lengths of installed system. Low thermal gradients develop across horizontal lengths of high temperature zones in landfills thus providing limited internal heat transfer and high thermal energy extraction potential. The zone that is impacted by the heat management systems can be controlled through length of installation. In addition, systems can integrate conductive and insulative zones through selection of materials adjacent to the heat management system components to further refine the control of heat transfer.

Vertical systems can be installed subsequent to waste placement when the waste mass reaches a certain height, whereas horizontal systems most practically can be installed while the waste mass is being placed. In general, installation of the vertical systems would be less complicated than the horizontal systems with relatively easy access to the waste in place as well as lack of direct interference with waste placement operations. Placement of a heat management system can be coordinated with installation of a gas collection system for construction scheduling. Heat management strategies are directly influenced by the timeline for installation and operation of the systems. Large early peaks and high temporal variations are present in heat generation rate functions for wet wastes with smaller peaks and less time-dependent variations present in dry wastes (Hanson et al., 2008). Horizontal systems can start operating while the waste mass is being placed at an early stage of waste disposal, whereas vertical systems become operational some time after waste disposal. Therefore, extraction, regulation, or supplementation can be initiated at an earlier stage using the horizontal systems than vertical systems.

3. Example heat management analyses

Example data and analysis are provided to demonstrate the application of the heat management strategies and associated energy calculations. Analysis is provided for two landfills. The first landfill is located in Michigan, U.S.A. with long-term temperature data and significant heat gain in the waste mass and elevated temperatures between 50 and 60 °C up to 65 °C measured over long durations (Yesiller et al., 2005; Hanson et al., 2010). The second landfill is located in New Mexico, U.S.A. with long-term temperature data and moderate heat gain in the waste mass and elevated temperatures between 30 and 38 °C measured over long durations (Yesiller et al., 2005; Hanson et al., 2010). Climate statistics for the two sites are presented in Table 1.

Temperature variations along horizontal and vertical profiles through the waste masses were investigated at the two landfills. Data were analyzed for three cells at the Michigan landfill (horizontal profile in Cell I; vertical profiles in Cells D and J) and two cells at the New Mexico landfill (horizontal profile at Cell 1–2 Border; vertical profile in Cell 1). The configurations of the temperature sensors were:

- In Michigan, the horizontal temperature sensor array in Cell I extended 133 m from the perimeter edge of the cell towards the middle of the cell, the array was overlain and underlain by 14 m and 16 m of waste, respectively, and the age of waste analyzed was 6 years. The vertical temperature sensor array in Cell D extended the entire 31.5 m depth from the cover to the

Table 1
Climatic conditions at the landfill sites.

Parameter	Michigan[a]	New Mexico[a]
Climatic zone and description[b]	Dfb: Cold-without dry season, warm summer	BSk: Arid steppe cold
Average daily high temperature (°C)	14.7	25.1
Average daily low temperature (°C)	5	11.2
Average daily temperature (°C)	9.8	18.2
Annual normal precipitation (mm)	835	240
Annual normal snowfall (mm)	1046	135
Mean annual earth temperature (°C)	13.6	20.9

[a] From NCDC (2016).
[b] Using Koppen-Geiger climate classification (Peel et al., 2007).

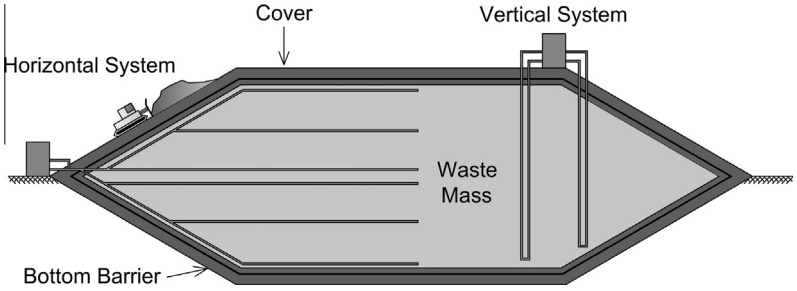

Fig. 3. Heat management systems.

bottom liner and the age of waste analyzed was 0–3 years; the vertical temperature sensor array in Cell J extended to a depth of 28 m at a location with a total waste column height of 38 m and the age of waste analyzed was 5–7 years.

- In New Mexico, the horizontal temperature sensor array along the border between Cells 1 and 2 extended 186 m from the perimeter edge of the cell towards the middle of the cell, the array was overlain and underlain by 14 m and 10 m of waste, respectively, and the age of waste analyzed was 1–3 years. The vertical temperature sensor array in Cell 1 extended to a depth of 12 m at a location with a total waste column height of 19 m and the age of waste analyzed was 3–5 years.

Calculations were made for extracting heat above unheated baseline conditions, $T_{(x,t)}$, and optimum temperature conditions for maximum gas generation, T_{LFG}. For determining $T_{(x,t)}$, a thermal diffusivity, α, of 5×10^{-7} m^2/s was used for both sites (Hanson et al., 2008). Details for determination of unheated baseline $T_{(x,t)}$ are presented in Yesiller et al. (2015a,b). T_{LFG} was selected as 35 °C for the analysis provided herein. For determining heat energy, volumetric heat capacity values of 2.00 MJ/m^3 K and 1.20 MJ/m^3 K were used for the landfills in Michigan and New Mexico, respectively, based on data provided in Hanson et al. (2008).

Results of the analysis are presented in Figs. 4 and 5. Data are presented for variation of $\Delta T_{avg\text{-}(x,t)}$ and $\Delta T_{avg\text{-}LFG}$ with location (horizontal distance or depth from perimeter edge). For the

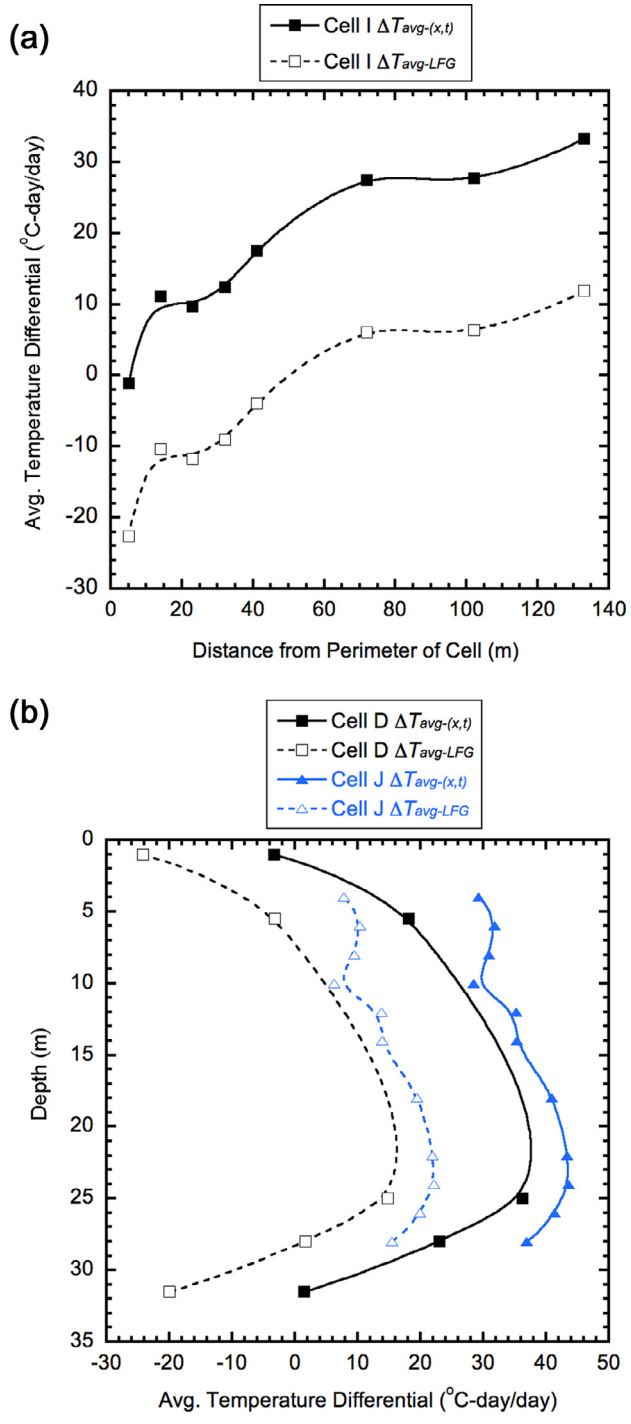

Fig. 4. Variation of average temperature differential with location at the Michigan landfill. (a) Horizontal profile and (b) vertical profile.

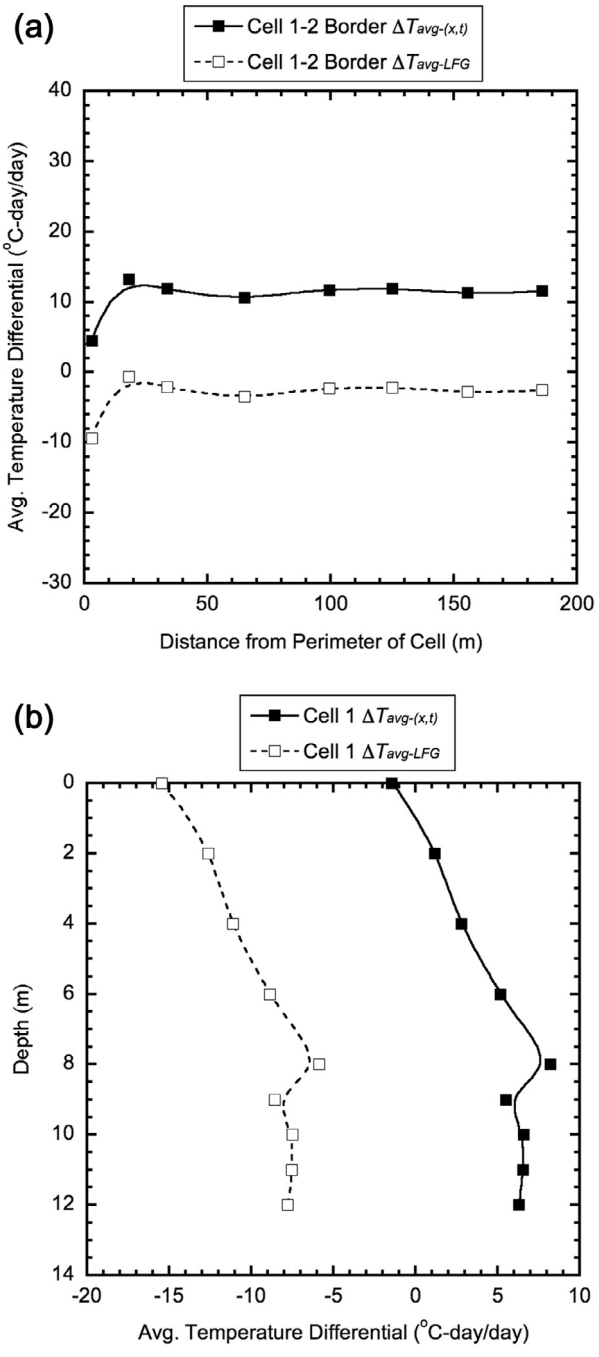

Fig. 5. Variation of average temperature differential with location at the New Mexico landfill. (a) Horizontal profile and (b) vertical profile.

horizontal systems, the $\Delta T_{avg\text{-}(x,t)}$ and $\Delta T_{avg\text{-}LFG}$ varied from −22.6 to 33.4 °C-day/day in Michigan (Fig. 4a) and from −9.3 to 13.3 °C-day/day in New Mexico (Fig. 5a). Higher values were observed for $\Delta T_{avg\text{-}(x,t)}$ and $\Delta T_{avg\text{-}LFG}$ in Michigan than New Mexico, in line with the higher waste temperatures. Also, more spatial variation in data was observed for Michigan. For the vertical systems, the $\Delta T_{avg\text{-}(x,t)}$ and $\Delta T_{avg\text{-}LFG}$ varied from −24.2 to 43.5 °C-day/day in Michigan (Fig. 4b) and from −15.5 to 8.2 °C-day/day in New Mexico (Fig. 5b). The spatial variation in data also was higher for Michigan than New Mexico. The observations related to spatial variation of the data agree with the thermal regimes provided in Fig. 2, where Michigan is an example of a landfill located in a cold and wet climate and New Mexico represents a landfill located in a warm and dry climate.

For the Michigan site (Cell D and Cell J), the trends of $\Delta T_{avg\text{-}(x,t)}$ and $\Delta T_{avg\text{-}LFG}$ were similar, yet higher values were present in the older wastes (5–7 years, Cell J) than younger wastes (0–3 years, Cell D). The increases were attributed to accumulation of heat with time. At locations near the top or edge of the landfills that are affected by seasonal temperature variations and at the base of the landfill with temperatures at or near mean annual earth temperature, the waste temperatures were at times below target temperatures. Therefore, negative average temperature differential values were present.

Next, available thermal energy, E_h, was calculated for the two sites and presented in Table 2. The weighted averages of temperature with distance along a given profile (horizontal or vertical) represent the uniform temperature (i.e., T_{cons}) that can be attained along the profile using the heat regulation strategy. T_{cons} calculated for the sites analyzed also are presented in Table 2. The calculated E_h and T_{cons} values demonstrate a wide range of conditions as a function of climatic region and operational practices. The E_h values demonstrated greater range (both higher maximum values and lower minimum values) in Michigan than in New Mexico. The higher E_h values were attributed to high precipitation, high waste placement rates, and high compacted unit weight of wastes in Michigan. The lower minimum E_h values in Michigan were attributed to climatic effects near the exposed boundaries of the waste mass (e.g., perimeter slopes). The T_{cons} values for the three Michigan Cells were above T_{LFG} (ranged from 35.8 to 49.8 °C) and the T_{cons} values for the two New Mexico Cells were below T_{LFG} (25.5 and 32.3 °C). Therefore, in general to reach T_{LFG} would require heat extraction (E2) at the Michigan site and would require heat supplementation (S2) at the New Mexico site.

A photograph of a pilot vertical heat management system installed at a landfill in the U.S.A. is presented in Fig. 6. The system components were constructed using plastic tubing and water was used as the heat transfer fluid. Details related to system construction and system operation as well as preliminary data are presented in Yesiller et al. (2016). The data obtained from the system indicate heat extraction at field scale. For operation on an intermittent basis over a duration of approximately 1 year, temperature decreases up to approximately 20 °C were observed near the heat extraction well. Recovery of temperatures to pre-extraction levels during nonoperational periods also was observed.

Fig. 6. Photograph of pilot heat management system.

Data from a pilot system installed at a landfill in Hungary were presented in Faitli et al. (2015), which also demonstrated feasibility of heat extraction at field scale.

4. Discussion

4.1. Application of heat extraction strategy

In the extraction heat management strategy, extracting all of the excess heat above baseline equilibrium conditions (i.e., $T_{(x,t)}$) in a MSW landfill system versus extracting only a part of the excess heat above equilibrium conditions to obtain target optimum waste temperatures for maximum landfill gas generation (i.e., T_{LFG}) have distinctly different implications for management of the landfill facility. For the first case (E1), alternative energy production from a landfill facility would be mainly resulting from the heat energy. Gas production would be diminished to a large extent under sub-optimal conditions. Such a strategy may be used permanently at a given facility. The need for a gas collection and extraction system would potentially largely be eliminated, in particular at sites with relatively low biological activity/gas production capacity by extracting excess heat above baseline unheated waste conditions. For landfills located in warm climates with high $T_{(x,t)}$ and sites with high biological activity/gas production potential, an auxiliary gas management system may be required. Nevertheless, a heat extraction system would be the main alternative energy production method used at a site.

Table 2
Calculated E_h and T_{cons} at the landfill sites.

Site	Minimum E_h from $T_{(x,t)}$ (MJ/m^3)	Maximum E_h from $T_{(x,t)}$ (MJ/m^3)	Minimum E_h from T_{LFG} (MJ/m^3)	Maximum E_h from T_{LFG} (MJ/m^3)	T_{cons} (°C)
Michigan Cell I (horizontal)	−2.3	66.7	−45.2	23.8	35.8
Michigan Cell D (vertical)	−6.6	72.4	−48.4	29.6	36.4
Michigan Cell J (vertical)	29.2	43.5	15.6	44.2	49.8
New Mexico Cell 1–2 Border (horizontal)	5.4	15.9	−11.2	−0.7	32.3
New Mexico Cell 1 (vertical)	−1.7	9.9	−18.6	−7.0	25.5

In E1 strategy, the heat extraction to target baseline unheated conditions can be used temporarily or at periodic intervals at a facility. The timing of gas production can be adjusted by manipulating and controlling the waste temperatures. The need for installation and operation of a gas collection and removal system may be delayed and adjusted by extracting excess heat above $T_{(x,t)}$. Both a heat extraction system and a gas collection system would be used at a facility, if the waste temperature is reduced to $T_{(x,t)}$ over predetermined target durations shorter than the gas and heat producing lifetime of a facility.

In the case of maintaining optimum waste temperatures for maximum gas generation (E2), a gas extraction system would be used together with a heat extraction system. The amount of heat energy extracted would be diminished compared to extraction to unheated conditions, while gas production would be maximized. Both a gas extraction system and a heat extraction system would be used at a site as alternative energy production systems. The gas generating lifetime of a MSW landfill facility would be affected by the optimum temperature conditions for production of landfill gas. Operation of a facility at T_{LFG} would result in higher amount of waste settlement compared to maintaining waste temperatures at $T_{(x,t)}$ due to enhanced decomposition of the waste mass and increased compressibility of the waste mass at T_{LFG} compared to $T_{(x,t)}$, similar to laboratory observations of increased amounts and rates of settlement with increasing temperature (Lamothe and Edgers, 1994).

4.2. Application of heat regulation strategy

In the regulation heat management strategy, landfill gas remains the main alternative energy source from a landfill facility. The R1 approach would result in enhanced gas generation, similar to the E2 strategy without the use of the heat extraction process. The enhanced gas generation would result in more waste settlement compared to no heat redistribution conditions at the landfill. The timing and duration for optimum gas generation at a landfill can be controlled by manipulating the waste temperatures with the heat redistribution approach. The timing of and duration for uniform waste temperatures at the T_{LFG} level can be adjusted to control and manipulate onset, duration, and magnitude of landfill gas generation. The heat regulation strategy allows for maximizing depth (or zone) over which landfill gas generation occurs at an optimal rate.

By regulating the waste temperatures at a target temperature (R2), biochemical or chemical processes occurring within the waste mass may be delayed or enhanced. In addition, mechanical processes such as waste settlement can be affected. Both biochemical and mechanical processes can be accelerated or decelerated for given landfill operational constraints.

4.3. Application of heat supplementation strategy

In the supplementation heat management strategy, addition or removal of heat have distinctly different implications for management of the landfill facility. The heat supplementation approach S1 provides opportunities for initiating and promoting biochemical activity, particularly during the initial lag phase of bacterial growth if cool and/or dry conditions prevail in a waste mass. The heat supplementation approach S2 provides opportunities for remediating excessive heat generation at a landfill or for arresting biochemical activity to provide a controlled period of low landfill gas generation in the landfill life cycle. Numerical simulations were conducted by Hanson et al. (2006) for a landfill in a cold climate, where season-specific (distinctly hot and cold) waste placement conditions were modeled. The difference in final thermal regime (i.e., temperature profile with depth) was significantly different based on this analysis indicating potential applicability of the supplementation strategies (S1 and S2) for manipulating landfill temperatures and heat generation.

In S1 strategy, the heat addition to target conditions can be used temporarily or at periodic intervals at a facility to reach and maintain target elevated temperatures. The temperatures raised to high levels with active heating at the onset of waste filling can be used to kick-start gas production. The production lifetime of a gas collection and removal system may be reduced by accelerating onset of gas production and maintaining optimal temperatures for gas generation. Both a heat supplementation system and a gas collection system would be used for this strategy.

In S2 strategy, the heat removal and active cooling process can be used temporarily or at periodic intervals at a facility to reach and maintain target reduced temperatures. In S2 strategy, the active cooling of the waste can be used for a variety of functions including reaching and maintaining optimal temperatures for gas generation (when existing waste temperatures are significantly above optimum conditions); reaching and maintaining low temperatures to delay waste decomposition and therefore postpone the need for installation of a gas collection system; and alleviating problematic hot zones in landfills. Both a heat supplementation system and a gas collection system would be used at a facility. The timing for installation or use of a gas collection system may be impacted through thermal control.

4.4. Operational considerations

Operation in line with the heat extraction, regulation, or supplementation strategy may be continuous or intermittent. To accelerate reaching a target temperature level or to maximize heat extraction magnitude or rate, a system may be operated on a continuous basis. Intermittent operation may be selected to be used or required to be used to reestablish optimum decomposition and heat generation conditions. Net thermal energy available (for E1, E2, and S2 approaches) or net thermal energy required (for S1 and S2 approaches) may exist locally. Specifically, thermal energy required for approaches S1 and S2 may be available through heat exchange with adjacent activities or processes. Examples of heat sources include excess heat available from landfill flare system or from nearby industrial operations. Examples of heat sinks available include stormwater or leachate retention basins or industrial processes requiring heat. The levels and rates of exchange for local heat energy inputs/outputs may be used as parameters for system design and operation of a landfill heat management system. Some sources of thermal energy (for S1 and S2) may be continuous, whereas others may be intermittent. Similarly, some uses for heat energy output from the landfill may be continuous whereas others may be intermittent or seasonal. Regular access to the heat management system and monitoring of thermal conditions would be required for operation and maintenance of the system for both continuous and intermittent applications.

The selection and use of a particular heat management strategy would be dictated by site-specific conditions including operational constraints as well as financial considerations. The amount of waste in place, rate of waste placement, type and presence of different cover types, and leachate management operations (particularly recirculation) would affect heat management. Constraints and barriers to heat extraction, regulation, or supplementation may be present based on prescriptive requirements from applicable regulatory schema. Detailed analyses would be required to assess the implications of installation and use of a heat extraction, heat redistribution, or heat supplementation system. In addition, for heat extraction, options for end use of the extracted heat would need to be evaluated. For selection between the three strategies, costs associated with design, installation, and operation of the

extraction, regulation, or supplementation system would need to be compared for a given site based on incoming waste quantities, general management strategies, and local climatic conditions. When enhanced gas generation conditions are present (strategies E2, R1, and S1, and strategy S2 for very high waste temperatures), the gas collection and extraction systems need to be designed for the added gas loading. The accelerated gas production may impact return on investment for large capital expenditure for installation of a gas collection system. Similarly, the potential cost savings due to gas collection infrastructure modifications and timing of installation that is realized through thermal control may in itself provide economic justification for use of a heat management system.

Experimental analyses need to be conducted to describe coupled heat and gas generation in landfill systems. Microbial biodegradation and heat generation are fully coupled processes in that biologically mediated degradation of organic matter results in heat generation and at the same time the biological processes are temperature dependent. Short- and long-term implications of extraction, regulation, and supplementation strategies need to be assessed experimentally and numerically. Predictions need to be made to estimate onset, duration, magnitude, and rate of heat generation for site-specific conditions similar to Hanson et al. (2008, 2013). Thermal energy balances need to be conducted for the proposed heat management systems. Modeling and pilot scale laboratory and field studies are required to verify the effectiveness and feasibility of design, installation, and operation of heat management systems in MSW landfills. Site-specific data and analyses are required to determine/estimate the temperatures, thermal properties, and overall heat generation potential at a given site. In addition, material and system configuration specifications including component material, component sizing, heat transfer fluid properties and flow regimes, and spacing of system components need to be established on a site-specific basis. Mechanical efficiency of the system and its components also need to be determined for successful operation of a heat management system.

As presented in Sections 2.1–2.3 and 3, semi-empirical approaches (supported by experimental and numerical analyses) are recommended to investigate heat generation and transfer processes in MSW landfills due to the difficulties associated with accurately estimating heat generation using theoretical biochemical degradation analyses. Such analyses would require accurate knowledge of the type and amount of incoming organic matter and spatial and temporal placement history of the organic matter at a facility. Semi-empirical approaches based on multi-dimensional heat generation and transfer analysis with consideration to thermal properties of the wastes, heat extraction system components, and heat exchange fluids can be used to establish the required parameters for design and operation of a heat management system.

Use of landfill heat as an alternative energy source represents a new approach for obtaining energy from MSW landfill facilities. Data on significantly elevated temperatures above unheated baseline waste conditions indicate the high potential for beneficial use of the excess landfill heat as an alternative energy source. The lifetime of gas collection and gas-to-energy systems is finite ending with the completion of decomposition of the organics and associated gas production. In contrast, heat extraction systems can be operated in perpetuity at geothermal heat extraction conditions (e.g., using ground source heat pumps) subsequent to the end of heat generation stage at a landfill when the landfill naturally returns to $T_{(x,t)}$ thermal conditions. Overall, the heat management strategies presented herein are developed to provide advancements in energy and process management for MSW landfills.

5. Summary and conclusions

Heat management strategies are presented to control individual heat generation processes or coupled heat and gas generation processes in MSW landfills. Heat is a primary byproduct of landfilling of municipal solid waste with elevated waste temperatures and significant amounts of heat generation reported in the literature. However, very limited analysis is presented for management of the heat generated in landfill systems. The conceptual framework proposed for management of landfill heat consists of three main strategies: extraction, regulation, and supplementation with two approaches in each strategy. Heat extraction (E1 and E2) is developed for beneficial use of the excess landfill heat as an alternative energy source. Heat regulation (R1 and R2) is developed to control the waste temperatures to achieve uniform distribution at target levels at a given landfill facility. Heat supplementation (S1 and S2) is developed to actively control the landfill thermal regime using external thermal energy sources to achieve target waste temperatures. The suggested strategies afford use of heat as an energy source as well as control of biochemical and geomechanical processes for operation of a landfill as a highly engineered system.

Operation of a heat management system at a landfill is highly site- and system-configuration-specific. Heat generation was analyzed for two sites in the U.S.A.: Michigan and New Mexico. Waste temperatures and resulting $\Delta T_{avg\text{-}(x,t)}$ and $\Delta T_{avg\text{-}LFG}$ values were higher in Michigan than in New Mexico. At the Michigan site, older waste (5–7 years old) had accumulated more heat than younger waste (0–3 years old). The available thermal energy, E_h, and overall average waste temperature, T_{cons}, were variable as a function of system orientation (horizontal versus vertical) and site (Michigan versus New Mexico). The E_h was additionally a function of system operation mode ($T_{(x,t)}$ or T_{LFG}). The calculated E_h ranged from -48.4 to 72.4 MJ/m^3 in Michigan and from -18.6 to 15.9 MJ/m^3 in New Mexico. For heat regulation, the T_{cons} ranged from 35.8 to 49.8 °C in Michigan and from 25.5 to 32.3 °C in New Mexico. Michigan had higher E_h than New Mexico for both $T_{(x,t)}$ and T_{LFG} modes of operation as well as higher T_{cons}. In general, to reach T_{LFG} would require heat extraction (E2) at the Michigan site and would require heat supplementation (S2) at the New Mexico site.

Factors that influence application of heat management strategies include availability of access points to the waste mass for installation of a management system; layout and sizing of system network; materials used for system components; timing of installation and operation of a management system; mode of operation (continuous or intermittent); rate and magnitude of extraction, regulation, or supplementation; end use for extracted heat; availability of thermal sources for supplementing heat; local climatic conditions; heat generation of waste; and cumulative coupled effects of heat management on biochemical and geomechanical processes in a landfill. The amount of waste that can be placed in a given volume of landfill over a given amount of time can be increased with accelerated decomposition and gas generation processes, providing both environmental benefits by reducing need for new landfill space and economic benefits by increasing revenue from waste placement. Overall, significant advancements are possible in management of MSW landfills by controlling operational waste temperatures and temperature-dependent processes, controlling and improving gas generation processes, and extracting and using excess heat as an alternative energy source.

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