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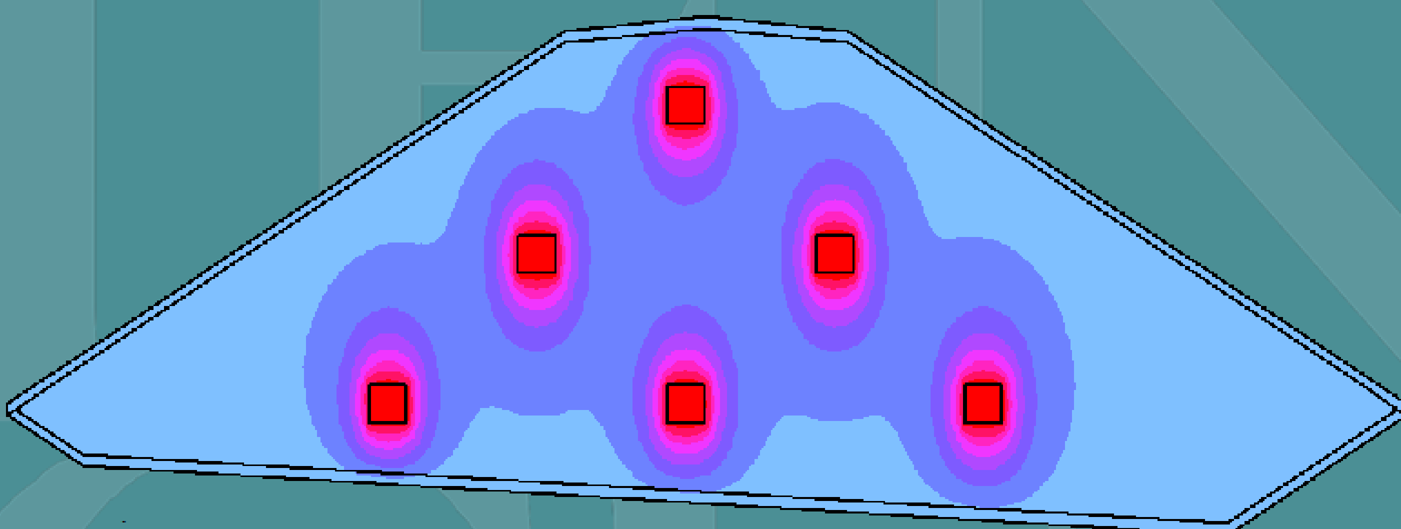
Modeling Thermal Changes at Municipal Solid Waste Landfills: A Case Study of the Co-Disposal of Secondary Aluminum Processing Waste



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Modeling Thermal Changes at Municipal Solid Waste Landfills: A Case Study of the Co-Disposal of Secondary Aluminum Processing Waste

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Foreword

The US Environmental Protection Agency (US EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under the mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, US EPA's research program is providing data and technical support for solving environmental problems today and building the scientific knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigating technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods of and their cost-effectiveness for preventing and controlling pollution of air, land, water, and sub-surface resources; protecting water quality in public water systems; remediating contaminated sites, sediments, and ground water; preventing and controlling indoor air pollution; and restoring ecosystems. NRMRL collaborates with public and private sector partners to foster technologies that reduce the cost of compliance and anticipate emerging problems. NRMRL's research provides solutions to environmental problems by developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by US EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Cynthia Sonich-Mullin, Director
National Risk Management Research Laboratory

Executive Summary

The reaction of secondary aluminum processing waste (referred herein to as *salt cake*) with water has been documented to produce heat and gases such as hydrogen, methane, and ammonia (US EPA 2015). The objective of this project was to assess the impact of aluminum salt cake disposal on municipal solid waste (MSW) landfill waste temperature distribution. Literature-reported properties of MSW and salt cake reactivity data were used in a model to assess how thermal properties of the waste materials and various salt cake waste placement scenarios. Material specific data would have to be provided if materials other than salt cake is to be evaluated could impact the temperature of the waste.

Because of the narrow range, MSW thermal conductivity had limited impact on the waste temperature (e.g., elevated heat generation rate). Ambient and ground temperatures (independent of salt cake placement) were found to have a moderate impact on waste temperature. The specific heat capacity and the heat generation rate of the mixed waste (i.e., containing both salt cake and MSW) were found to have the most significant effect of all the properties evaluated in this assessment. The landfill temperature increase following the co-disposal of salt cake with MSW was found to be directly proportional to the heat generation rate and inversely proportional to the heat capacity of the surrounding MSW fraction; heat capacity of a material is the amount of heat needed to increase its temperature by a unit degree. Several factors such as of the amount of salt cake (relative to MSW) and heat release timeframe influence the heat generation rate within the landfill. Because of its wider range, the heat generation rate is expected to have a greater influence on waste temperature within a landfill than any other factor.

Apart from the heat generation rate and heat capacity properties of the material, the model simulations predicted that the material placement strategy would have a significant impact on the spatial distribution of waste temperature within a landfill. The simulated placement of salt cake in single or multiple discrete pockets resulted in localized high heat generating zones with temperatures in excess of 190°C (374°F). As a point of reference, Title 40 of the Code of Federal Regulations, Part 60, Subpart WWW requires the operation of landfill gas collection systems to maintain landfill gas well temperatures below 55°C (131°F). Temperatures above 55°C may indicate air infiltration and can lead to an elevated risk of a landfill fire. The placement of the material at the surface or uniformly mixed with MSW resulted in a lower maximum predicted waste temperature of 50-70°C (122-158°F). However, surface placement of salt cake may adversely impact landfill closure-cap integrity and fugitive gas

emission. The role of leachate and landfill gas movement (i.e., convective modes of heat transport) in heat removal from and the resultant temperature distribution within a MSW landfill was found to be insignificant.

Stabilizing the salt cake by reacting it with water and exhausting its heat and gas generation potential before co-disposal with MSW should be explored. This approach may provide opportunities to beneficially recover the heat and combustible gas generated during salt cake waste reactions while mitigating the unintended consequences to landfill infrastructure that may occur at an MSW landfill.

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Notice

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Table of Contents

List of Tables

List of Figures

List of Abbreviations, Acronyms, and Initialisms

%	Percent
°C	Degrees Celsius
°F	Degrees Fahrenheit
2-D	Two dimensional
AK	Alaska
ASTM	American Society for Testing and Materials
C	Specific heat capacity of waste, ($kJ\ kg^{-1}\ K^{-1}$)
C_p	Volumetric heat capacity ($kJ\ m^{-3}\ K^{-1}$)
C_{pf}	Fluid heat capacity, ($kJ\ kg^{-1}\ K^{-1}$)
cm	Centimeter
FEMA	Federal Emergency Management Agency
ft	Feet
FL	Florida
g	Gram
GCCS	Gas collection and control system
HDPE	High-density polyethylene
IA	Iowa
J	Joules
K	Kelvin
K_c	Thermal conductivity, ($W\ m^{-1}\ K^{-1}$)
kg	Kilogram
kJ	Kilojoules
L	Liter
LFG	Landfill gas
LLDPE	Linear low-density polyethylene
m	Meters
m^3	Cubic meters
mL	Milliliter
mm	Millimeter
MSW	Municipal solid waste
MT	Metric Ton
NFIRS	National Fire Incident Reporting System
NRMRL	National Risk Management Research Laboratory
NSPS	New Source Performance Standards
ρ	Waste density, ($kg\ m^{-3}$)
PVC	Polyvinyl chloride
Q	Heat generation rate of the waste, ($W\ m^{-3}$)
s	Second
t	Time
T	Temperature
U_f	Gravimetric fluid flux, ($kg\ s^{-1}\ m^{-2}$)
US	United States
US EPA	United States Environmental Protection Agency
v/v	Volume per volume
W	Watts ($J\ s^{-1}$)
X	Cartesian coordinate

Definitions

Boundary Condition - In this study, includes temperature and (for convective heat transport modeling) pressure specified at the top (including the slopes) and bottom surfaces of the modeled landfill geometry.

Conduction - The flow of heat by the transport of energy from one soil particle to another through physical contact or through immobile pore fluids. This definition is adopted from Geoslope (2014).

Convection - The process that transports heat from a surface when exposed to fluids (leachate or landfill gas) of a different temperature flowing over it. This definition is adopted from Geoslope (2014).

Heat Capacity - Amount of heat required to raise the temperature of a unit amount of material by 1 degree (°F or °C or °K).

Heat Flux - Heat flow rate per unit area

Initial Condition - In this study, refers to the starting temperature of the landfilled waste (and salt cake) used in transient simulations.

Thermal Conductivity - The quantity of heat that flows through a unit area (i.e., heat flux) of a material of unit thickness in unit time under a unit temperature gradient.

Transient - Time dependent

1 Introduction

1.1 Background

Based on an analysis of fire incidents reported by the National Fire Incident Reporting System (NFIRS), an average 836 fires occur annually at municipal solid waste (MSW) landfills in the U.S. (NFIRS 2004 – 2011). The causes of fires in landfills, which may emerge as a surface reaction or a sub-surface reaction, are varied and may include spontaneous combustion or self-ignition, loads that are smoldering when initially disposed of in the landfill, human causes (e.g., arson or accidents such as discarding lit cigarettes), and disposal of wastes that cause substantial heat generation (Amon et al. 2012; Moqbel 2009; FEMA 2002). Together, the heat generated from biological reactions, the effects of heat-producing wastes, and the insulating nature of landfilled waste can lead to a transition into highly exothermic chemical reactions that lead to either fires or fire-like reactions such as pyrolysis (Moqbel 2009).

Fires or significant heat-generating reactions at landfills are a concern for a multitude of reasons, including human health and safety, impacts to the stability of the landfill, and damage to the protective infrastructure (e.g., bottom and top liner systems, leachate management systems, and gas collection systems). While little information exists regarding the specific mechanisms and dynamics of sub-surface reactions that may lead to fires, recent studies identified reaction of aluminum species present in secondary aluminum processing waste as a potential source of landfill fire. The research presented in this report assesses the impact of secondary aluminum processing waste (i.e., salt cake) disposal on heat generation and transport, and the resultant temperature distribution in an MSW landfill. The project also evaluates the impact of various factors such as ambient temperature, heat generation rate, waste thermal properties, and operational strategies (e.g., segregation of waste types, liquids addition, active gas extraction) on landfilled waste temperature.

1.2 Project Objectives and Report Organization

The objective of the project was to assess the impact of salt cake disposal on the waste temperature distribution in MSW landfills. The impact of salt cake disposal on MSW landfill temperature distribution was numerically modeled. Heat is released from the reaction of salt cake with water (US EPA 2015). Salt cake heat generation potential data based on a US EPA (2015) laboratory-scale study were used to estimate the heat generation rate from salt cake. These estimated heat generation rates were used as inputs for modeling thermal dynamics resulting from salt cake disposal in MSW landfills using TEMP/W®[1], a finite element computer program used for modeling heat transport in porous media. TEMP/W® simulations were also coupled with a companion program, AIR/W® (Geo-Slope International Ltd.) to assess the impact of landfill gas flow on waste temperature distribution in landfills; AIR/W® is a finite element software that models air flow in porous media. The impacts of heat generation rate, thermal conductivity, heat capacity, and moisture content on the temperature distribution in a MSW landfill were analyzed. The impacts of different salt cake disposal strategies (e.g., placement near the landfill surface, placement in several discrete pockets scattered throughout the landfill) were analyzed as well.

The report is organized in six sections. Section 1 provides a brief introduction and outlines the objectives and scope of the research. Section 2 presents the fundamentals of heat generation and transport in MSW landfills along with a description of previous studies that investigated landfill heat transport. Section 3 presents the modeling approach methodology used in this research. Section 4 presents the modeling results and a discussion of the model outputs. Section 5 summarizes the results and discusses broad conclusions

[1] GEO-SLOPE, GeoStudio, SEEP/W, TEMP/W, AIR/W, and their logos are trademarks or registered trademarks of GEO-SLOPE International, Ltd. in Canada and/or other countries.

from the project. Section 6 presents the references used during this project. Supplemental information is provided in an appendix.

1.3 Quality Assurance and Control Plan

This project entailed the collection and analysis of secondary data. The appropriateness of the data and their intended use was assessed with respect to data source, data collection timeframe, and the scale of the experiments used for data generation. Preference was given to data from well-developed, peer-reviewed reports/papers (e.g., those published in government reports and peer-reviewed journals) over information that had not undergone a peer review process (e.g., conference proceedings, trade journal articles, personal estimates). Data from field-scale experiments were preferred over those from laboratory-scale data. Preference was given to more recent data over older data. The report includes the sources of all data and identifies any data limitations.

2 Fundamentals of Heat Generation and Transport in MSW Landfills

2.1 Waste Temperature

A literature review was conducted to identify the temperature of MSW deposited in landfills, temperature ranges that may create sub-surface fires, and temperature ranges that can impact the service life and performance of landfill infrastructure. In a survey of 22 landfills that reported sub-surface fires, disposal of high-temperature loads (e.g., smoldering materials) was identified as one of the primary causes of sub-surface fires (Moqbel 2009). Heat generation from salt cake deposited in MSW landfills can potentially create high temperature conditions similar to those of high-temperature loads that may cause sub-surface fires. Apart from subsurface fires, elevated temperatures also compromise the service life and performance of landfill infrastructure such as gas collection pipes and geomembranes (Rowe et al. 2010). Repairing the damage to these components can be time and cost intensive.

Unlike other monitoring parameters (e.g., landfill gas quality, leachate quantity and quality), in-situ waste temperature is typically not monitored at landfill sites. The only monitoring requirement pertaining to temperature at landfills is the New Source Performance Standards (NSPS), which prescribe a limit of 55°C for landfill gas at the well head for MSW landfills. When gas temperature at a collection well exceeds this value, the landfill operator must take corrective actions (e.g., reducing the gas extraction vacuum at the well, providing additional soil cover in the area, placing a protective boot around the well to limit the infiltration of ambient air). According to the background document for NSPS (US EPA 1995), this temperature threshold was selected as it represents a temperature that “may indicate a problem” regarding either sub-surface fires or inhibition of anaerobic decomposition.

Although dependent on in-situ waste temperature, landfill gas temperature at the well head should not be used as a proxy for waste temperature for several reasons (Martin et al. 2011). First, the measured temperature at a wellhead reflects the temperature of gas collected from various depths in the landfill. (Well screens are typically at least 6 m deep and can reach more than 50 m deep for vertical wells). Second, the atmospheric temperature strongly influences the gas temperature at the gas well head; the well head is exposed to and not thermally insulated from the atmosphere. Thus, the temperature of the waste itself is expected to be greater than the temperature of the gas measured at the wellhead. Figure 2-1 presents a comparison of the in-situ waste temperature and gas temperature data set from an MSW landfill in the US with an active gas collection and control system (GCCS). The in-situ waste temperature profile was measured using thermocouples installed at 20 ft intervals. The gas collection well is located 25 ft from the thermocouple cluster. As Figure 2-1 shows, the in-situ waste in some cases far exceeds (by 70%) the measured temperature of the landfill gas. Daily and weekly monitoring data were used to estimate the 2-month average in-situ waste and gas well temperatures, respectively.

Table 2-1 summarizes various adverse conditions resulting from elevated temperatures, the associated temperature for which the adverse condition was/could be noticed, and the source of information. As shown in Table 2-1, multiple studies cited that temperatures in the range of 60 - 88°C (140 - 190°F) can result in adverse conditions such as the chemical oxidation of waste, waste ignition, subsurface fires, and deterioration of the functionality of landfill infrastructure installed within landfilled waste (e.g., the maximum service temperature of a schedule 80 pipe, commonly used for gas well construction, is 60°C (140°F)). The infrastructure outside the landfill (e.g., closure cap) may also be compromised due to subsidence resulting from subsurface combustion of deposited waste. Based on laboratory-scale experiments, Moqbel (2009) reported the auto-ignition temperature (i.e., temperature at which a material self-ignites without any ignition source) of dry waste constituents to range from approximately 204 to 431°C; the auto-ignition temperature of dry MSW was reported to be 267°C.

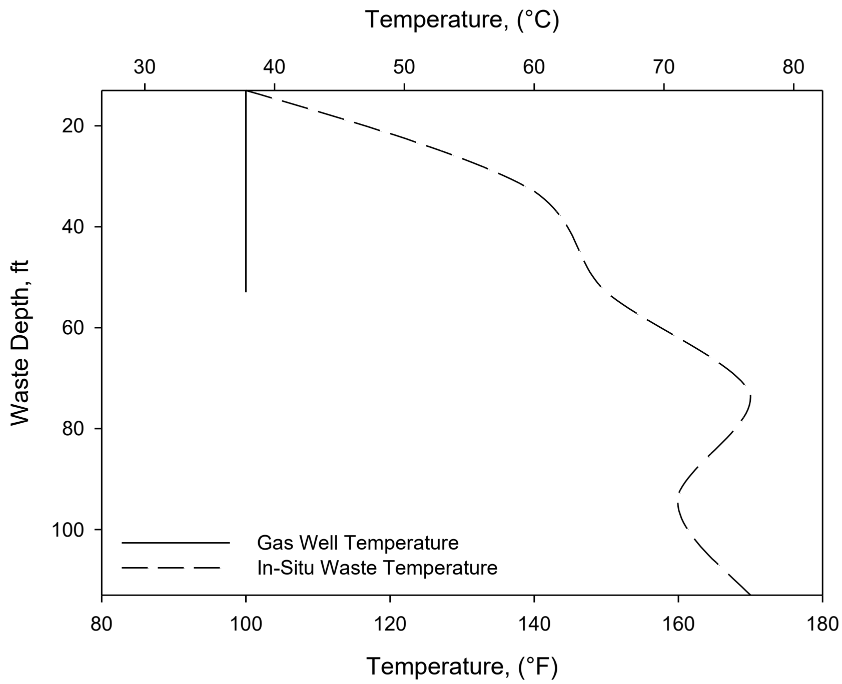


Figure 2-1. Comparison of In-situ Waste Temperature and Temperature Measured at a Gas Well at a MSW Landfill Site

In summary, although a large set of temperature measurements for landfill gas is available due to regulatory requirements, in-situ waste temperature data are scarce. As a result, no reliable numerical criteria have been established for differentiating between warm versus hot waste temperatures or threshold temperatures indicative of pyrolysis, a sub-surface fire, an exothermic event, or a similar classification.

Table 1. Adverse Impacts and the Associated Temperatures

Condition	Temperature	Description	Source
Subsurface fire	>77°C (170°F)	Lists this threshold temperature as one general criterion (of six) for confirming the presence of a landfill fire.	FEMA (2002), CalRecycle (2006)
Subsurface fire	88°C (190°F)	An experimental aerobically operated cell achieved temperatures as high as 190°F at 10 and 16-ft depths before thermistor loss and observance of landfill fire.	Merz and Stone (1970)
Waste ignition	>65°C (149°F)	Combustible waste (especially low flash point materials) can easily ignite above this temperature when air is introduced.	Lewicki (1999) (as described in Bates (2004))
Chemical oxidation of waste	60 - 71°C (140 - 160°F)	As temperatures surpass this range, it is suggested that chemical oxidation plays a dominant role in heat generation. As discussed, a continuous source of oxygen is needed for heat generation to continue to the point of waste ignition.	Sterns and Petoyan (1984)
Auto-ignition	204 - 431°C (400 - 808°F)		Moqbel (2009)
Schedule 80 PVC pipe service temperature	60°C (140°F)	Schedule 80 PVC pipe is documented to have a maximum service temperature of 140°F.	Harvel (2014)
HDPE pipe softening temperature	125°C (257°F)	The softening temperature of HDPE piping from the ASTM D – 1525 testing method.	ISCO (2014)
HDPE and LLDPE geomebrane liner maximum exposure temperatures	60 - 71°C (140 - 160°F)	Cited as the maximum exposure temperature that HDPE and/or LLDPE can withstand before a dramatic decrease in service life.	WMW (2013), GSE (2014)

2.2 Mathematical Model to Simulate Transport in Landfills

The following equation has been used to model heat transport in landfilled waste and porous media (Domenico and Schwartz 1990, El-Fadel et al., 1996a and Berglund, 1998):

$$\frac{\partial^2 T}{\partial x^2} - \frac{U_f C_{pf}}{K_c}\frac{\partial T}{\partial x} = \frac{C\rho}{K_c}\frac{\partial T}{\partial t} - \frac{Q}{K_c} \quad (1)$$

where T is temperature (K), K_c is thermal conductivity (W m^{-1} K^{-1}), U_f is gravimetric fluid (e.g., landfill gas, leachate) flux (kg s^{-1} m^{-2}), C is the specific heat capacity waste (kJ $kg^{-1}K^{-1}$), C_{pf} is the specific fluid heat capacity (kJ kg^{-1} K^{-1}), ρ is waste density (kg m^{-3}), t is time (s), x is a Cartesian coordinate, and Q is the heat generation rate of the waste (W m^{-3}). Table 2-2 summarizes input variables needed to simulate heat transport in landfills analytically or numerically.

Table 2. Input Parameters to Simulate Heat Transport in Landfills

Input Parameters	**Details Presented in Section**
Heat Generation rate, Q	2.4.1
Specific heat capacity of waste, C	2.4.2
Thermal conductivity, K_c	2.4.3
Waste density, ρ	2.4.2
Gravimetric fluid flux, U_f (only for convective heat transport)	4.7
Specific heat capacity of fluid, C_{pf} (only for convective heat transport)	4.7

This chapter presents a brief description of previous studies that investigated heat transport in landfills with a primary objective of compiling waste thermal properties used or measured by these studies. Only details specific to waste thermal properties and other pertinent modeling details such as boundary conditions used in these studies are presented in this section.

2.3 A Review of Previous Heat Transport Modeling Related Studies

El-Fadel (1996a) modeled the sequential waste decomposition process and the associated heat and gas generation and transport in a landfill. Both conductive and convective modes of heat transport were modeled; however, heat convection associated with liquids flow was not modeled. Conduction is the flow of heat by the transport of energy from one soil particle to another through physical contact or through immobile pore fluids. Convective heat transfer is the process that transports heat from a surface when exposed to fluids (leachate or landfill gas) of a different temperature flowing over it. These definitions are adopted from Geoslope (2014). The heat generation rate was modeled as directly proportional to the waste decomposition rate (specifically, the acetic acid generation rate).

The weighted average thermal conductivity; heat capacity; and density of solid, liquid and gas phases were used for modeling in El-Fadel (1996a). The ambient and ground temperatures were used as the temperature for the top and bottom of the landfill, respectively. The model used the estimated temperature as an input for the biological decomposition reaction rate calculation and gas transport modeling. El-Fadel (1996b) used the model to compare the modeling results to the data from an experimental landfill cell.

Berglund (1998) modeled one-dimensional conductive and convective heat transport from landfilled waste. Only the convective heat flow associated with liquid flow was modeled; convection associated with gas flow was not modeled. It appears that the data collected by Berglund (1995) were used in conjunction with analytical modeling to estimate the heat generation rate. Berglund (1998) does not provide details such as model, thermal diffusivity, and specific heat capacity used for modeling.

Thomas and Ferguson (1999) modeled conductive-convective heat flow in a landfill to assess the impact of thermal gradients on sub-surface migration of landfill gas (LFG) through an engineered clay liner. Thermal conductivity, heat capacity, and density of waste used for modeling were 0.5 W m^{-1} K^{-1}, 0.6 kJ kg^{-1} K^{-1}, and 1,600 kg m^{-3}, respectively; these values were based on literature-reported values.

Hanson et al. (2000) estimated thermal properties of various granular materials, including solid waste, using experimental methods (needle-probe and dual-probe methods) and analytical methods (amplitude and phase changes and estimation of the total heat capacity based on heat capacity values of individual components) and reported that experimental and analytical methods provided similar thermal diffusivity values. The thermal conductivity of MSW measured using the needle-probe method was reported to range from 0.01 - 0.7 W m^{-1} K^{-1}. The heat capacity measured using the dual-probe method was reported to range from 800 to 10,000 kJ m^{-3} K^{-1}.

Lefebvre et al. (2000) measured the thermal conductivity of 23 samples collected from a landfill in France using a thermal shock probe. The measured thermal conductivity ranged from approximately 0.04 - 0.22 W m^{-1} K^{-1} (estimated from data presented in Figure 8 of the paper). The average thermal conductivity was reported to be 0.1 W m^{-1} K^{-1}. The volumetric heat capacity was calculated from the measured thermal conductivity and diffusivity. The average volumetric heat capacity was reported to be 600 kJ m^{-3} K^{-1}. Due to a lack of details of the experimental method, the quality of the reported thermal conductivity and diffusivity data could not be evaluated.

Nastev et al. (2001) modeled temperature-dependent LFG flow, leachate, and conductive-convective heat transport in a landfill using TOUGH2-LGM to assess the impact of various factors such as barometric temperature fluctuation and active LFG collection on fugitive LFG emission. Heat generation was assumed to be 40 kJ per mole of methane and carbon dioxide generation. A heat capacity of 1,333 kJ kg^{-1} K^{-1} was used for modeling. Thermal conductivities of 0.038 and 0.184 W m^{-1} K^{-1} were used for dry and wet waste, respectively. The thermal conductivity and heat capacity values were reported to be taken from literature. Based on the gas collection flow rate and quality data of four cells at a landfill site in Canada, the gas generation potential of the waste was estimated to be 172 m^3 per MT; assuming a methane content of 55% (by volume), the methane generation potential was estimated to be 94.6 m^3 methane per MT of waste.

Klein et al. (2003) modeled one-dimensional conductive heat transport in an MSW incinerator ash monofill to assess the temperature at the bottom liner. A bi-exponential decay model was used for simulating the impact of a time-varying heat generation rate. Based on the analysis, Klein et al. (2003) concluded that the risk of liner damage due to elevated temperatures can be substantially reduced by temporarily storing ash for a period prior to disposal in a lined monofill cell. Thermal properties used by El-Fadel et al. (1996a, 1996b, and 1997) were used for modeling. Modeling results were compared with the temperature measurements from two ash monofills in Germany.

Yesiller et al. (2005) analyzed the temperature data collected at four MSW landfill sites (the same as those used by Hanson et al. (2008)) to assess the impact of various factors such as waste placement rate, initial waste temperature, ambient temperature, and waste depths on waste temperature and heat content. Yesiller et al. (2005) reported thermal gradient, heat content, and heat generation rate estimates based on data collected at the four sites. Heat content was found to conform to an exponential growth and decay curve relationship based on operational and climatic conditions. Conductive heat losses were estimated using a vertical heat transfer analysis with a thermal conductivity of 1 W m^{-1} K^{-1}; the basis of this assumption regarding thermal conductivity used for modeling was not provided. A volumetric heat content of 2,000 kJ m^{-3} K^{-1} was reported based on the experimental data and published literature. Heat generation was estimated to range from 23 to 77 MJ m^{-3}. Convective heat losses were approximated based on leachate collection data. The conductive heat losses were determined to be significantly greater than convective heat losses from leachate removal. The analysis did not include convective heat losses associated with LFG flow.

Neusinger et al. (2005) numerically modeled (using CFX-4) heat transport in a landfill to assess the impact of waste depth, heat generation rate, water content, and cap imperfections on temperature distribution in a landfill. A heat generation rate of 1 W m^{-3} and a thermal conductivity of 1 W m^{-1} K^{-1} were used for modeling; a heat generation rate of 1 W m^{-3} was described as typical for landfills in Germany.

Kindlein et al. (2006) numerically analyzed heat transport in landfilled waste as part of a coupled biochemical transformation and multiphase transport model. Although convective heat transport is not exclusively included in the heat transport equation, it appears that convective heat transport associated with leachate and gas movement was modeled. The predicted temperatures were used as an input for modeling reaction kinetics and phase transformation occurring within the system. Thermal conductivity and specific heat capacity values of waste used for modeling were 3.4 W m^{-1} K^{-1} and 1.3 kJ m^{-3} K^{-1}, respectively. A rationale for the use of these values or their sources were not provided.

Gholamifard et al. (2008) modeled the landfill biological decomposition process coupled with liquids, gas, and heat generation and flow. The decomposition was modeled as a function of system temperature and saturation. The heat generation rate used in modeling was derived from the hydrolysis and the methane production rates. These heat production rates were estimated as 170 kJ $mole^{-1}$ of volatile fatty acid produced and 80 kJ $mole^{-1}$ of methane produced. The ambient temperature (ranging from 2 - 26°C (35.6-78.8°F) (over one year) and a temperature of 10°C (50°F) were used as the temperature for the top and bottom of the landfill, respectively. Temperature profile data from two bioreactor landfills in France were analyzed in conjunction with the modeling results to estimate the thermal conductivity and heat capacity. The thermal conductivity values of 0.8 W m^{-1} K^{-1} and 1 W m^{-1} K^{-1} provided a best fit to the field-measured temperature data in numerical modeling. The waste heat capacity was estimated to range from 0.9 - 1.1 kJ kg^{-1} K^{-1}.

Hanson et al. (2008) numerically modeled conductive heat flow and developed an analytical model using ABAQUS (v 6.5). The modeling results were analyzed with long-term temperature measurements at four landfill sites in North America to develop an analytical equation for predicting the heat generation rate as a function of time. Literature-reported thermal conductivity values were used for modeling. The heat capacity was estimated based on heat capacity values of individual waste constituents and waste composition as reported by the US EPA.

Meima et al. (2008) summarizes MSW heat capacity estimates found in the literature. Rowe et al. (2010) used a finite volume-based computational fluid dynamic code, FLUENT, to model a typical landfill liner system and to analyze a hypothetical cooling system that could be installed at the time of landfill construction. Heat generation information was estimated by comparing the modeled temperature with temperature data from the base of the Tokyo Port Landfill. The model included conduction and liquid-flow convective processes. The heat generation rates for waste exposed to air, wet waste, and dry waste were estimated to be 4.67, 0.436, 0.763 W m^{-3}, respectively. Thermal conductivities of 0.35 and 0.96 W m^{-1} K^{-1} were used for waste above and below the leachate level, respectively. Heat capacities of 1.94 and 2.36 kJ kg^{-1} K^{-1} were used for waste above and below the leachate level, respectively. The thermal conductivity and heat capacity used for waste were reported to be based on Yoshida and Rowe (2003). Yoshida and Rowe (2003) did not provide additional detail on the sources of these data.

In summary, several studies have modeled heat transport in landfills for a variety of objectives including simulation of the MSW decomposition process and for assessing the impact of elevated temperature on liner system integrity. Only a handful of studies have undertaken estimation or measurement of MSW thermal properties, which are key inputs to heat transport modeling. MSW thermal properties, as found in peer-reviewed literature, are summarized in Table A-1. The thermal properties used for the modeling scenarios conducted during this study are included in Table A-2.

2.4 Thermal Properties of MSW and Salt Cake

2.4.1 Heat Generation for MSW and Salt Cake

In MSW landfills, heat is released during the different stages of organic matter degradation, but the majority of the heat released from anaerobic organic matter biodegradation is associated with acetic acid production (El-Fadel et al. 1996b). It is reasonable to consider that heat release resulting from organic waste decomposition may be directly correlated with LFG production, since both heat and gas are products of biodegradation. El-Fadel et al. (1996a) used the following equation to estimate the heat generation from anaerobic digestion, where the heat generation is estimated as 244.5 kcal per mole of converted organic matter.

$$(C_6H_{10}O_5)_2 + 14H_2O \rightarrow 8HCO_3^- + 4CH_4 + 8H^+ + 8H_2 + \text{Heat}$$

Figure 2-2 presents a box-and-whisker plot of the heat generation rate for MSW reported in the literature (Hanson et al. 2008, Rowe et al. 2010); a tabular compilation of these values and their sources are presented in Appendix A. A box-and-whisker plot provides a visual portrayal of the statistical distribution of the data. The line inside the box represents the median. The top of the box represents the 75th percentile and the bottom of the box represents the 25th percentile. When present, the limits of the lines that extend upward and downward (whiskers) from the box represent the 90th and 10th percentiles, respectively. Sufficient data points were not available to display the whiskers and outliers for the heat generation rate; at least 9 data points are needed to estimate the 10th and 90th percentile values.

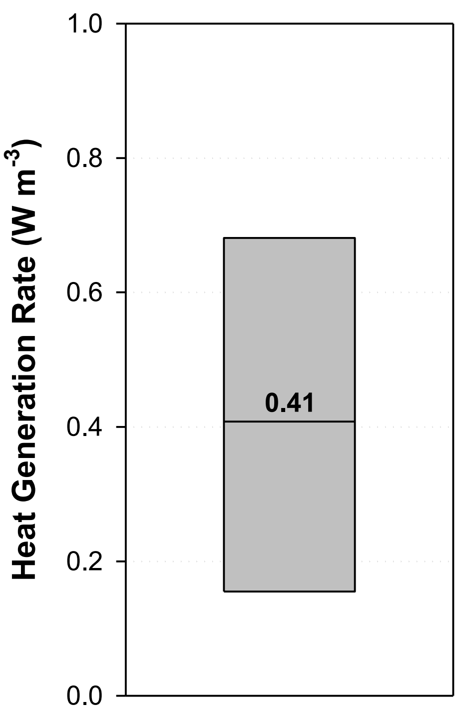


Figure 2-2. Distribution of Literature-Reported MSW Heat Generation Rate Values

Only Hanson et al. (2008) and Rowe et al. (2010) estimated heat generation ranges based on temperature measurements from landfills; the upper and lower limit of these ranges is included in Figure 2-2. Some sources only provide the heat generation potential (total heat released per waste volume), while others report heat generation relative to gas production (heat energy released per mole of gas produced). These values were not included in Figure 2-2. The median of the heat generation rate values reported in the literature was estimated to be 0.41 W m^{-3} (35.3 kJ day^{-1} m^{-3}), which is equivalent to 5.1×10^{-4} W kg^{-1} (0.044 kJ day^{-1} kg^{-1}) assuming an in-place MSW (without salt cake) density of 800 kg m^{-3}.

Apart from biological decomposition of MSW, heat generation may also occur from exothermic chemical reaction of industrial waste constituents such as salt cake with water or gases present in a landfill. As discussed earlier, the primary focus of this report is salt cake, which is a byproduct of secondary aluminum processing and releases significant heat when reacted with water.

US EPA (2015) reported the heat generation potential of salt cake based on a series of laboratory-scale experiments conducted on samples from 10 facilities in the US; multiple samples were tested for each facility. A double-walled calorimeter was used to measure the total heat released during the reaction of size-reduced salt cake with deionized water. The space between the inner and outer vessel was filled with ethylene glycol and contained three thermocouples used to take temperature readings every 2 minutes. Ports installed in the upper Teflon cap of the calorimeter allowed the injection of preheated liquid (10 mL for the 5-g sample of ground-up salt cake) and allowed the escape of gas produced from the reaction. Sand samples were included with each batch of samples as a control group. With these measurements, a calibration curve was constructed that compared the difference in temperature between the salt cake and sand using the temperature readings to estimate the heat generation potential (i.e., the total heat release of the reaction).

The heat generation potential of individual samples was reported to range from 0.2 - 3.6 kJ g^{-1} (US EPA 2015). The mean heat generation potential for each facility ranged from 0.43 to 2.8 kJ g^{-1}. Figure 2-3 presents the distribution of the mean heat generation potential values of each of the 10 facilities. The average of the mean heat generation potential values for each facility was 1.0 kJ g^{-1}. Assuming that 100% of the heat is released in 1 month, 1 year, and 10 years, the heat generation rates are estimated to be approximately 0.39, 0.032, and 0.0032 W kg^{-1} (33.3, 2.74, and 0.274 kJ day^{-1} kg^{-1}), respectively. These estimated heat generation rates are significantly greater than those reported for MSW. However, salt cake typically constitutes a small fraction of the total waste landfilled for facilities that accept salt cake.

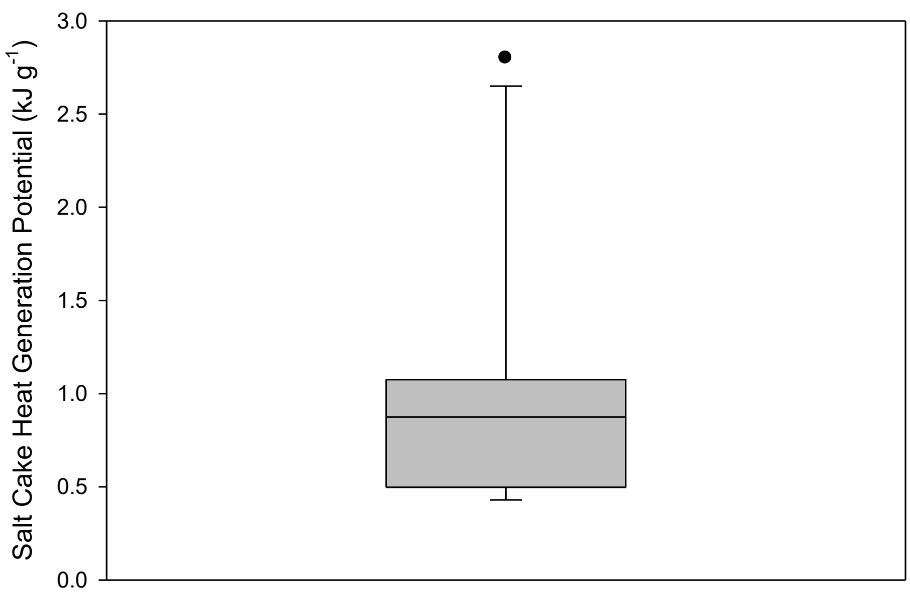


Figure 2-3. Salt Cake Heat Generation Potential Measured by the US EPA (2015)

A reasonable estimate of the timeframe over which 100% of the heat is released from salt cake is critical to estimate the heat generation rate and simulate the resulting landfill temperature distribution. Heat is primarily released from reaction of water with the aluminum present in salt cake. Reaction stoichiometry suggests that 108 kg (108 L) of water is needed for approximately 54 kg of aluminum (Calder and Stark 2010). US EPA (2015) analyzed the total metal content of salt cake samples as part of a previous project and estimated that aluminum constitutes approximately 14% of salt cake by weight. Therefore, 108 L of water will be needed to complete the exothermic reaction with approximately 386 kg of salt cake. In other words, approximately 0.28 L of water would be needed per kg of salt cake. If salt cake constitutes 5% of the total waste landfilled, 0.014 L of water is needed for 1 kg of total waste deposited, which is equivalent to a gravimetric moisture content of 1.4% (wet-weight basis). The literature-reported moisture content (wet-weight basis) of US landfilled waste has been reported from 3.5 to 76.4%, with values commonly in the 20 to 30% range (Townsend et al. 2015); a 20% moisture content (wet-weight basis) was assumed to be representative of typical MSW. Although 100% of the moisture in the landfill may not be available to react with salt cake due to factors such as non-uniform moisture and salt cake distribution, it appears that a one-year timeframe for the completion of the heat generating reaction is not an unreasonable assumption.

To assess the impact of salt cake disposal on the overall heat generation rate from landfilled waste, the total weighted average heat generation rate for mixed MSW and salt cake was estimated assuming that salt cake represented 0, 5 and 10% of the total waste mass disposed of in the landfill. The heat generation rate of MSW was chosen as the median value reported in the literature presented above (i.e. 5.1×10^{-4} W kg^{-1}). The weighted average heat generation rate is shown in Figure 2-4 for each of the three assumed salt cake-water reaction timeframes. As can be seen from Figure 2-4, the salt cake heat generation rate has a significant impact on the total heat generation rate of the landfill waste even for the case where heat is released over a 10-year timeframe and where only a small fraction of the landfilled waste is salt cake. For example, the overall heat generation rate quadrupled with disposal of 5% salt cake by weight and a 1-year heat release timeframe (compared to a 1-year heat release timeframe with 0% salt cake).

In the absence of data on the actual heat generation rate from landfill-deposited salt cake and its variation over time, it was assumed that all the heat from salt cake will be uniformly released in one year. The heat release from salt cake was assumed to occur once the landfill is built-out. In reality, heat generation from the salt cake may start as soon as it is placed in the landfill and a significant fraction of its total heat generation potential may be exhausted due to exposure to precipitation and the associated surface runoff before it is covered with more waste. The waste temperature developed in this case would be lower than those associated with modeled cases where heat generation is assumed to begin after the salt cake is covered with layer(s) of waste insulating it from the ambient environment. The heat generation rate was assumed to be independent of the waste temperature.

Further, based on discussions with industry representatives, it was assumed that 5% (by weight) of the waste disposed of in a landfill is salt cake for all the simulations conducted in this study. Using the median MSW heat generation rate and salt cake heat generation rate estimates above, the weighted average heat generation was estimated to be 2.1×10^{-3} W kg^{-1} (0.179 kJ day^{-1} kg^{-1}). The density of the composite waste (MSW and salt cake) was estimated to calculate the volumetric heat generation rates needed for modeling. Due to lack of density data, an in-place density of 2,200 kg m^{-3} was assumed for salt cake. The in-place MSW density was assumed to be 800 kg m^{-3}; a density of 800 kg m^{-3} was selected based on the compacted MSW density (in landfill) range reported by Tchobanoglous et al. (1993). The density of the composite was calculated to be approximately 826 kg m^{-3}. The volumetric heat generation of the composite waste was estimated using the weight-based average value from the two materials. The volumetric heat generation was estimated to be 1.735 W m^{-3} (148 kJ day^{-1} m^{-3}); a value of 150 kJ day^{-1} m^{-3} (1.74 W m^{-3}) was selected for modeling.

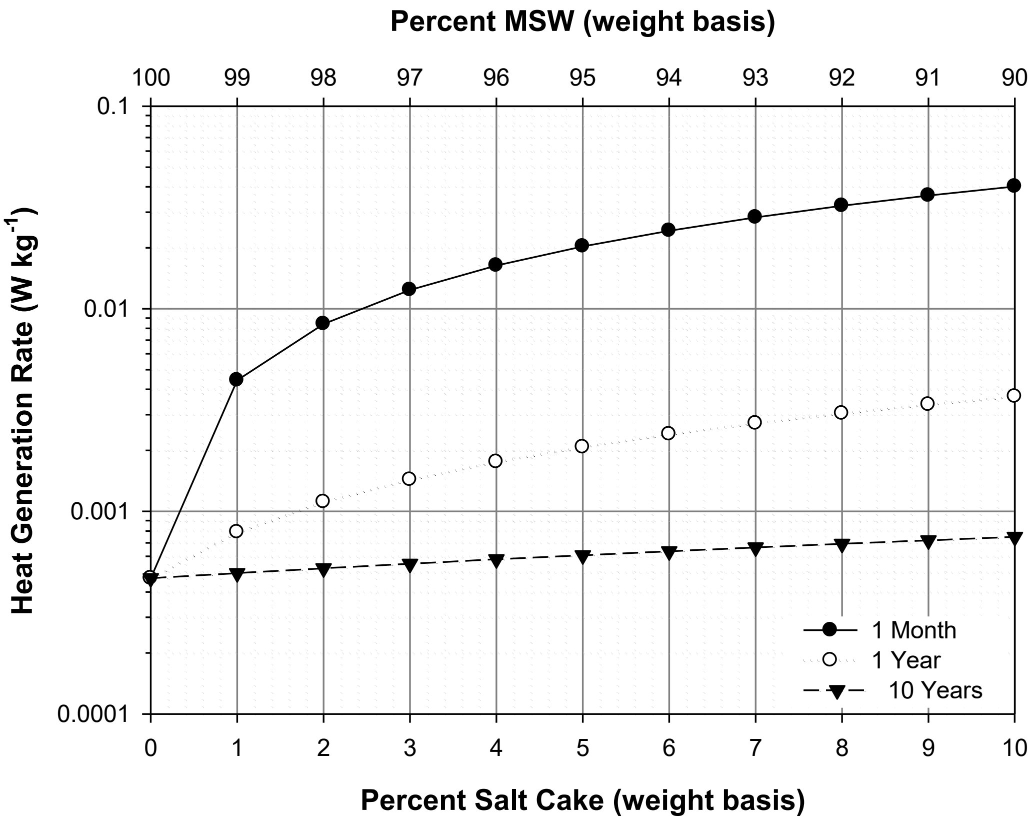


Figure 2-4. Weighted Average Heat Generation as a Function of MSW and Salt Cake Proportion Disposed of in an MSW Landfill Assuming Complete Salt Cake Degradation in Different Timeframes

2.4.2 Specific Heat Capacity

Specific heat capacity is the amount of heat required to raise the temperature of a unit amount of material by 1 degree (°F or °C or °K). Specific heat capacity is commonly presented in units of J kg^{-1} K^{-1}. It is a measure of a material's ability to store heat. For a given increase in temperature, materials with greater heat capacity can store a greater amount of heat than materials with lower heat capacity.

Figure 2-5 presents the distribution of heat capacity values for MSW reported or used by previous studies. Only Hanson et al. (2000), Lefebvre et al. (2000), and Gholamifard et al. (2008) estimated or measured the heat capacity for MSW. Other studies either used literature-reported values of the heat capacity of MSW or the estimate is based on heat capacity values of individual MSW constituents. The median of the MSW specific heat capacity values compiled from literature is approximately 1.33 kJ kg^{-1} K^{-1}, which is equivalent to a volumetric heat capacity of 1,040 kJ m^{-3} K^{-1} assuming an in-situ MSW density of 800 kg m^{-3}. It is assumed that this heat capacity value already accounts for the heat capacity associated with a 20% moisture content (wet-weight basis).

Specific heat capacities have been measured and reported for several materials (Miller and Clesceri 2003). Table 2-3 presents the specific heat capacity value of various materials commonly present in landfills (Miller and Clesceri 2003). As can be seen from Table 2-3, water (4.19 kJ kg^{-1} K^{-1}) has the greatest specific heat capacity among all the materials in landfills; therefore, for a given heat input, higher moisture content will result in smaller waste temperature increase. Table 2-3 also lists the heat capacities of materials used for liner and closure cap construction (geomembrane and geotextile). A density of 940 kg m^{-3} was used to convert the volumetric heat capacity estimated from the thermal conductivity and diffusivity values of these materials reported by Hoor and Rowe (2012).

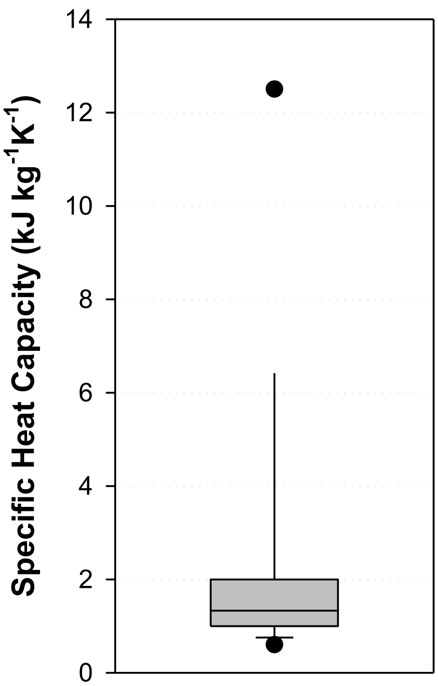


Figure 2-5. Distribution of Specific Heat Capacity Values of MSW Reported or Used in the Literature

Table 2-3 also presents the volumetric heat capacity and density used for estimating volumetric heat capacity; volumetric heat capacity is calculated by multiplying specific heat capacity and in-place density. The in-place density of the materials (except for clay, sand, geomembrane, geotextile, air, and water) were estimate based on as-collected density and compaction factors reported by Tchobanoglous et al. (1993). The volumetric heat capacity of most materials ranges from 320 to 1,500 kJ m^{-3} K^{-1}. The volumetric heat capacity of air is significantly lower than any other material present in the landfill, whereas the heat capacity of water is greater than all other materials present in the landfill.

The heat capacity for salt cake is also presented in Table 2-3. Information on the heat capacity (and thermal conductivity) of salt cake is limited. Only Li (2012) reported the thermal diffusivity and conductivity of salt cake based on a laboratory-scale study. Li (2012) estimated the thermal diffusivity of a salt cake sample in the laboratory based on the time taken by one end of a salt cake sample of known thickness to reach half its maximum temperature when the other end was subjected to laser irradiation. The thermal diffusivity was reported to be 0.87 mm^2 s^{-1}. Li (2012) reported salt cake thermal conductivities ranging from 5 - 6.1 W m^{-1} K^{-1} (425 – 525 kJ day^{-1} m^{-1} K^{-1}) depending on aluminum content. Due to the scarcity of information on salt cake, the midpoint of the thermal conductivity range presented in Li (2012) was chosen (475 kJ$day^{-1}m^{-1}K^{-1}$) for the modeling presented in this report and the heat capacity of salt cake was estimated based on the thermal diffusivity presented above. Using the values for thermal diffusivity and thermal conductivity provided by Li (2012), the volumetric heat capacity was estimated as 6,320 kJ m^{-3} K^{-1}, which is equivalent to a specific heat capacity of 2.87 kJ kg^{-1} K^{-1}. The weighted average specific heat capacity for composite waste (95% MSW and 5% salt cake by weight) was calculated to be 1.41 kJ kg^{-1} K^{-1}. The volumetric heat capacity and not the specific heat capacity is used as an input for heat transport modeling with TEMP/W®. The volumetric heat capacity of composite waste (using a density of 826 kg m^{-3} estimated above) was estimated to be 1,162 kJ m^{-3} K^{-1}. A volumetric heat capacity of 1,170 kJ m^{-3} K^{-1} was, therefore, selected for modeling.

Table 3. Specific and Volumetric Heat Capacity of Various Materials Present in Landfills†

Material	Specific Heat Capacity, C, (kJ kg^{-1} K^{-1})	In-place Density (kg m^{-3})	Estimated Volumetric Heat Capacity, C_p (kJ m^{-3} K^{-1})
Food waste	1.34 - 4.95	880	1,180 - 4,360
Plastic	1.38 - 2.30	650	900 - 1,500
Glass	0.66	490	320
Iron/Steel	0.632	1,070	680
Aluminum	0.934	1,070	1,000
Yard waste	1.34 - 2.5	510	680 - 1,280
Paper	1.34	600	800
Wood	2.09 - 2.30	790	1,650 - 1,820
Leather	1.507	540	810
Rubber	1.758	440	770
Textile	0.33	1,070	350
Air	1.00	1.00	1.00
Water	4.19	1,000	4,190
Clay/Silt	1.842	2,000	3,680
Sand/Gravel	0.795	2,000	1,590
Geomembrane	1.91	940	1,800
Geotextile	3.72	940	3,500
Salt Cake	2.87	2,200	6,320

2.4.3 Thermal Conductivity

Thermal conductivity characterizes the ability of a material (e.g., soil) to transmit heat by conduction. It is defined as the quantity of heat that flows through a unit area (i.e., heat flux) of a material of unit thickness in unit time under a unit temperature gradient. Figure 2-6 presents a distribution of MSW thermal conductivity values reported/used by previous studies; a compilation of these values is presented in Appendix A. Hanson et al. (2000) measured the thermal conductivity of MSW samples using a needle probe. Lefebvre (2000) also measured the thermal conductivity of 23 waste samples taken from landfills in France. Gholamifard et al. (2008) estimated thermal conductivity by curve-fitting the modeling results with the temperature measurements at two landfill sites in France. Apart from these three studies, all the other studies discussed earlier in the report used literature-reported values. The median of the thermal conductivity values found in literature as presented in Figure 2-6 is 0.375 W m^{-1} K^{-1}, which is equivalent to 32.4 kJ day^{-1} m^{-1} K^{-1}. It is assumed that this thermal conductivity value already accounts for the heat capacity associated with a 20% moisture content (wet-weight basis).

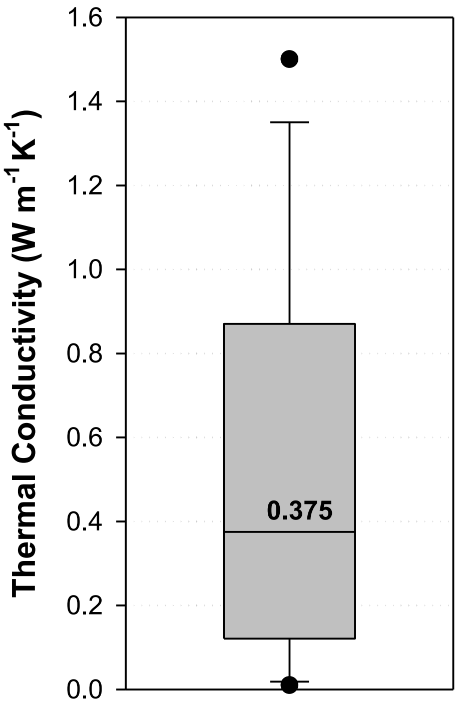


Figure 2-6. Distribution of Literature-Reported Values and Median for MSW Landfill Thermal Conductivity

The thermal conductivity of the mixed waste (95% MSW and 5% salt cake by weight) was calculated by taking a weighted average of the median thermal conductivity value of MSW reported in literature (0.375 W m^{-1} K^{-1}) and salt cake (5.5 W m^{-1} K^{-1}). The composite thermal conductivity was estimated to be 0.63 W m^{-1} K^{-1} (54.5 kJ day^{-1} m^{-1} K^{-1}) and this value was selected for modeling.

Table 2-4 presents the thermal conductivity of materials commonly present in a landfill (Miller and Clesceri 2003). Metals have significantly greater thermal conductivity than any other MSW constituent. The thermal conductivity of a majority of materials ranges from 0.05 - 0.33 W m^{-1} K^{-1}. The thermal conductivity values for geomembrane and geotextile are based on Hoor and Rowe (2012). The thermal conductivity of salt cake is based on measurements reported by Li (2012).

Table 4. Thermal Conductivity of Materials Commonly Present in a Landfill

Material	**Thermal Conductivity, K, (W m^{-1} K^{-1})**
Food waste	0.05
Paper	0.14 - 0.15
Plastics	0.16
Wood	0.128 - 0.186
Yard waste (Garden Waste)	0.05
Glass	0.8 - 1.1
Steel	55
Aluminum	202
Leather	0.14 - 0.17
Rubber	0.03 - 0.23
Textile	0.33
Clay	1.26 - 2.9
Sand	0.93
Air	0.025
Water	0.6
Geomembrane	0.45
Geotextile	0.7
Salt Cake	5.0 - 6.1

3 Heat Transport Modeling Approach

3.1 TEMP/W® and AIR/W®

TEMP/W® is a two-dimensional finite element software that models temperature distribution in porous media resulting from changes in environmental conditions (e.g., atmospheric temperature) or infrastructure (e.g., buildings, pipelines). The software can analyze both steady-state and transient (i.e., time dependent) conditions, apply boundary conditions to mimic actual environmental conditions, and specify thermal properties for a given geometry. It should be noted that, by itself, TEMP/W® only models conductive heat transport and does not model convective heat transport associated with leachate and/or landfill gas flow (via advection and or diffusion). AIR/W®, a SEEP/W® plug-in, can simulate convective heat transport in porous media when used in conjunction with TEMP/W®. Both conductive and convective modes of heat transport in a landfill can be modeled by coupling TEMP/W® with AIR/W® and SEEP/W®. More details on these models can be found elsewhere (Geoslope 2014).

3.2 Inputs Used for Modeling

Unless otherwise stated, the waste (95% MSW and 5% salt cake by mass) properties presented in Table 3-1 were used for modeling various scenarios to assess the impact of various factors on landfill heat transport and resultant temperature profiles. A summary of these scenarios is included in Section 3.6 and a detailed list of the thermal property values used in each scenario is included in Appendix A (Table A-2).

These properties are representative of the case where salt cake is uniformly distributed throughout the landfill. Although salt cake would likely be landfilled in discrete pockets, a uniform distribution throughout the landfill was assumed for a majority of simulations conducted in this report. This assumption potentially results in a lower resultant maximum temperature than that associated with salt cake disposal in discrete pockets as discussed later in the report.

Table 5. Waste Properties used for Modeling

Modeling Parameter	Value Used	Details Presented in Section
Heat Generation rate, Q	150 kJ day^{-1} m^{-3} (1.74 W m^{-3})	2.4.1
Volumetric heat capacity, C_p	1,170 kJ kg^{-1} K^{-1}	2.4.2
Thermal conductivity, K_c	54.5 kJ day^{-1} m^{-1} K^{-1} (0.63 W m^{-1} K^{-1})	2.4.3

TEMP/W® simulations were performed to assess the impacts of thermal conductivity and volumetric heat capacity on the temperature distribution within the landfill. For these simulations, the 10th, median, and 90th percentile values for each of the parameters were selected from the literature-reported range of values to assess the impact of these parameters on temperature distribution in the landfill. Six simulations were performed for a 1-year simulation time; three of these varied the heat capacity while holding the other parameters constant (i.e., at the median literature-reported value and LFG-derived heat generation rates), and three varied the thermal conductivity while holding the other parameters constant.

3.3 Landfill Geometry

TEMP/W® allows the specification of the 2-D geometry of the medium of study (i.e., landfilled MSW and salt cake) for the heat transport analysis. Figure 3-1 presents the cross-section of the MSW landfill modeled for all the simulations presented in this report, unless stated otherwise. The surrounding grades were assumed at a 7-m elevation. The bottom liner was assumed to slope at 5%; landfill bottom liners are sloped to promote gravity-drainage of the intercepted leachate to collection sump(s). The total width was assumed to be approximately 150 m. The side slopes were assumed to be 3:1 (horizontal:vertical). The top deck slope was assumed to be 5%. The maximum elevation of the top of the landfill was assumed to be at 28 m.

The bottom liner and closure cap thickness were assumed to be approximately 0.6 m. The geometry resulted in a maximum waste depth of approximately 26 m (~85 ft). As quantification of the maximum temperature resulting from salt cake reactivity was a primary objective of the simulations, temperature profiles were plotted for the landfill center (along A-A’ section in Figure 3-1), which was the region of the maximum waste temperature for a majority of the simulations.

A spatial discretization of 1 m in the horizontal and vertical direction was used for all the simulations. A time step of 1 day was used. As described earlier, it was assumed that all the heat from salt cake will be uniformly released over 1 year. As a result, the maximum temperature associated with the heat release from salt cake within the waste is expected to occur at the end of the first year temperature increase, if any after salt cake stabilization would be associated with the heat release from MSW.. All the simulations were conducted for 1 year unless otherwise stated.

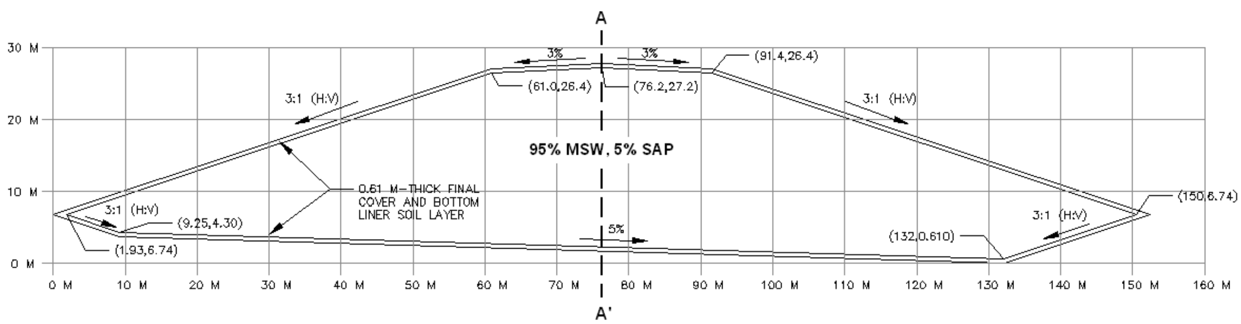


Figure 3-1. Geometry Layout of MSW Landfill Modeled in TEMP/W®

3.4 Boundary Condition

In addition to the waste properties (e.g., heat generation rate, thermal conductivity), the temperature at the waste boundaries (i.e., the landfill bottom and top surface including the slopes) impact heat transport within the landfill. The conditions specified at the landfill top and the bottom surfaces are referred herein to as the *boundary condition*. The bottom boundary was modeled as a constant-temperature boundary. The top surface (including sideslopes) is exposed to the atmosphere, so a time-varying ambient temperature was assigned (using the climatic data from the TEMP/W® data library) to the top surface of the domain modeled. It is noteworthy to mention that TEMP/W® allows for user-defined climate boundary conditions, However, that functionality was not used here. TEMP/W® uses these values to estimate heat transfer to the ground surface and to model the effects of snowfall accumulation and dissipation, if applicable. The default model climate data for Fairbanks (Alaska), Des Moines (Iowa), and Miami (Florida) were used to assess the impact of ambient temperature (sinusoidal distribution of ambient temperature was used) on temperature distribution in the landfill. The average annual ambient temperatures for Fairbanks, Des Moines, and Miami are -2.98, 9.7, and 24.8°C (27, 50, 77°F), respectively. Unless otherwise stated, climate data of Des Moines (Iowa) was used as representative climatic conditions in the US for all the simulations.

Since the landfill bottom surface (i.e., the base of the liner) was assumed to maintain a constant temperature, this boundary acted as a "sink" for the heat migrating towards this boundary for all the simulations. If the heat is not effectively removed by the soil beneath the bottom surface, the resultant elevated temperature will extend into and beneath the liner system. Due to the nature of the boundary condition used for the landfill bottom, the results presented in the report should not be used to evaluate the impact of elevated temperature on the liner system.

The volumetric heat generation rate (kJ day^{-1} m^{-3}) (including heat generation from both salt cake reaction and the biological decomposition of MSW, as described in Section 2.4.1) was assigned throughout the waste; no heat generation was assigned to the bottom liner and top cap materials. A series of simulations were conducted to assess the impact of landfill gas flow on the temperature distribution in the landfill. TEMP/W® was coupled with SEEP/W® and AIR/W® for these simulations. Constant air pressures were specified at the base and surface of the waste domain in AIR/W® to model air flow rate representative of the landfill gas generation rate estimates presented in Section 4.7 and the ensuing convective heat transport. AIR/W®'s default thermal conductivity and heat capacity for air were used as proxy for landfill gas for all the convective heat transport simulations.

3.5 Initial Conditions

Transient (time dependent) simulations were conducted for this study. Transient modeling requires specification of initial conditions (i.e., conditions at the start of the simulation time period). A steady-state (time independent) simulation was performed to estimate the initial waste temperature corresponding to each transient simulation. An annual average ambient temperature was assigned to the top (including side slopes) and a ground temperature was assigned to the bottom surface for the steady-state analysis. Heat generation from the waste was assumed to occur only for the transient modeling simulations; waste was assumed to not generate heat for the steady-state simulations.

3.6 Scenarios Modeled

Table 3-2 presents a list of conditions or scenarios modeled. Twenty-one simulations were conducted for the assessment presented in this report; a list of the simulations conducted along with the input parameter values used is presented in Appendix A.

Table 6. List of Scenarios Modeled

Condition/Scenario Modeled	Section Number
Impact of cap and bottom liner on waste temperatures	4.1
Impact of ambient and ground temperature on waste temperature	4.2
Impact of MSW thermal conductivity and heat capacity on waste temperature	4.3
Impact of moisture content on waste temperature	4.4
Impact of heat generation rate on waste temperature	4.5
Impact of disposal strategies on waste temperature	4.6
Impact of landfill gas collection on waste temperature	4.7

3.7 Assumptions

The section summarizes the global assumptions used for a majority of the simulations conducted in this study. Additional details about these assumptions are presented throughout Chapters 2 and 3. Deviations, if any, from these assumptions are discussed in relevant sections of Chapter 4. The following assumptions, unless stated otherwise, were used for the simulations:

1. Uniform distribution of salt cake throughout the landfill
2. The heat release from salt cake was assumed to commence after the completion of waste filling in the landfill cell. In other words, the heat generation was assumed not to begin until the salt cake is completely covered with layer(s) of waste insulating it from the ambient environment. In reality, heat generation from the salt cake may start as soon as it is placed in the landfill and a fraction of its heat generation potential may be exhausted due to exposure to precipitation and/or surface water

runoff before it is covered with more waste. The resultant waste temperature under these circumstances are expected to be lower than those associated with the conditions modeled. It was assumed that salt cake represents 5% (by weight) of the waste mass and all the heat from salt cake will be uniformly released in one year. The waste temperature, associated with salt cake reactivity, therefore, is expected to be the greatest at the end of one year. Therefore, except for the scenarios analyzing the impact of ambient and ground temperatures, a 1-year modeling timeframe was used for all the transient simulations.

3. The heat generation rate was assumed to be independent of the waste temperature.
4. Climatic conditions and ground temperature representative of Des Moines, Iowa, were used for the landfill top and bottom surfaces, respectively. The shallow groundwater temperature was assumed to reasonably approximate the ground temperature.
5. Only the conductive mode of heat transport was simulated for a majority of the simulations. A few simulations were conducted to assess the impact of the convective mode of heat transport on waste temperature.

4 Modeling Results and Discussion

4.1 Impact of Cap and Bottom Liner on Waste Temperature

Federal regulations require the installation of a bottom liner for MSW landfills, . MSW landfills that reach final grade are also required to install a final cover, designed to minimize the quantity of fugitive LFG released from the landfill's surface and minimize precipitation infiltration into the waste mass. Two TEMP/W® simulations were performed to analyze the effects of the cap and bottom liner layers on temperature distribution within the landfill.

Typical bottom liner and final cover systems (collectively referred herein to as the *containment system*) have three primary components: geomembrane, geotextile, and soil (e.g., compacted clay and sand; cover system typically also includes a top soil layer). Due to limitations of the model to assign a region of thickness of geotextile and geomembrane, the liner and cap were modeled as a 0.60-m-thick layer of a single material. For a conservative assessment, the thermal properties that would result in the least heat transport through the containment layer were selected for this layer. Material with lower thermal diffusivity, which is the ratio of thermal conductivity and volumetric heat capacity, allows lower heat conduction than materials with greater thermal diffusivity. Of the three components, geotextile has the lowest thermal diffusivity (refer to Tables 2-2 and 2-3 for the thermal conductivity and heat capacity of these materials). Therefore, geotextile thermal conductivity and volumetric heat capacity of 0.7 W m^{-1} K^{-1}, and 3,500 kJ m^{-3} K^{-1}, respectively, were used for the containment layers for one model while the composite waste (i.e., MSW and salt cake) thermal conductivity and heat capacity were assigned to the containment layers for the other model.

Figure 4-1 shows temperature distribution within the landfill with the containment system. As expected, the temperature in the center of the landfill is greater than any other zone as this area is farthest from the exterior sides, which are maintained at a lower temperature by the ambient and ground temperatures. This observation was, in general, true for all the simulations with uniform distribution of salt cake throughout the landfill. Temperature variations with depth at the centerline of the landfill were plotted to compare maximum temperature within the landfill with and without containment. Figure 4-2 shows the temperature profile over the waste depth at the center of the landfill. As presented in the figure (and subsequent figures) Q is the heat generation rate, C_p is the volumetric heat capacity, and K_c is the thermal conductivity. The temperature profiles with and without containment mostly overlapped each other, suggesting that the containment system does not impact heat flux. The higher thermal conductivity and relatively small thickness of the containment layers with respect to the waste are the potential reasons for the insignificant impact of the containment layers on waste temperature distribution. Due to its relatively lower thermal conductivity, waste is the limiting factor for heat flux. Due to its properties (i.e., relatively low permeability and high thermal conductivity compared to the waste) the containment layers restrict mass flux while allowing heat flux. All the subsequent simulations were conducted without containment layers; the containment layers were assigned the same properties as the waste.

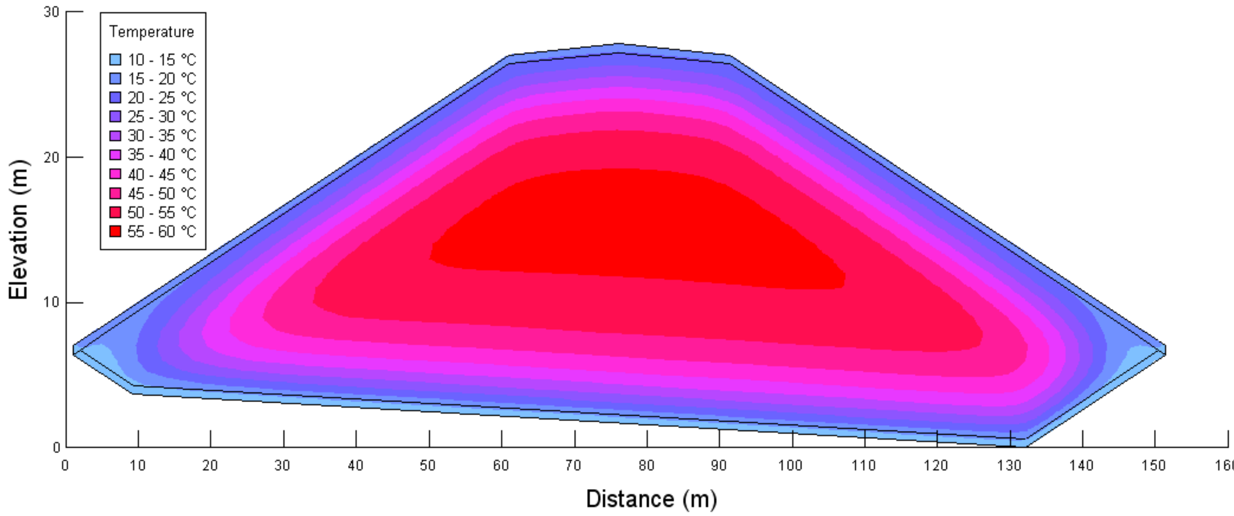


Figure 4-1. Temperature Distribution in the Landfill with Bottom Liner and Closure Cap

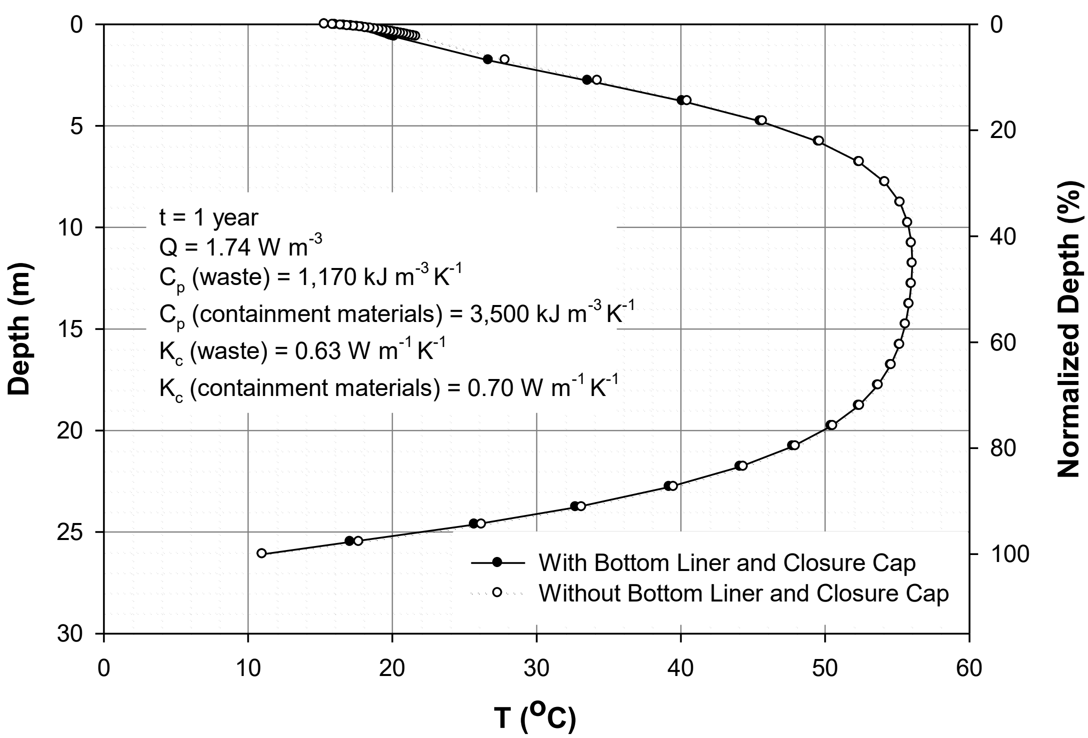


Figure 4-2. Comparison of Temperature Profiles with and without Containment Layers

4.2 Impact of Ambient and Ground Temperature

The temperature of the soil surrounding an MSW landfill's bottom liner is expected to be dependent on the geographic location. Figure 4-3 (taken from US EPA (2013)) presents the average shallow groundwater temperature distribution for the continental US. The shallow groundwater temperature varies from about 37 – 77°F (3 – 25°C) across the continental US. The shallow groundwater temperature can be reasonably assumed to approximate the ground temperature and studies have shown the ability to identify shallow groundwater depth based on surface temperature dynamics (Alkhaier et al. 2012a, Alkhaier et al. 2012b).

Three simulations were conducted to assess the simultaneous impact of the ambient and the ground temperature on temperature distribution within a landfill accepting salt cake. The ambient and ground temperatures for Fairbanks (Alaska), Des Moines (Iowa), and Miami (Florida) were used for these simulations to assess the impact of the range of ambient and ground temperatures encountered in the US. Constant annual average ground temperatures of 0°C (32°F), 11°C (51.8°F) and 22°C (71.6°F), respectively, were assigned to the landfill bottom surface for simulations for Fairbanks, Des Moines, and Miami, respectively. The ground temperature of Fairbanks was assumed to be 0°C (32°F) in the absence of state-specific data. The model-default, temporally-varying ambient temperatures for these cities were assigned as the surface temperature boundary condition for the landfill. The simulations for these scenarios were conducted for a period of 5 years to assess the impact of seasonal temperature variations. A composite waste (95% MSW and 5% salt cake) heat generation rate was used for the first year. Only an MSW heat generation rate was used for the subsequent four years as by the end of the first year the entire heat generation potential of salt cake is assumed to be exhausted.

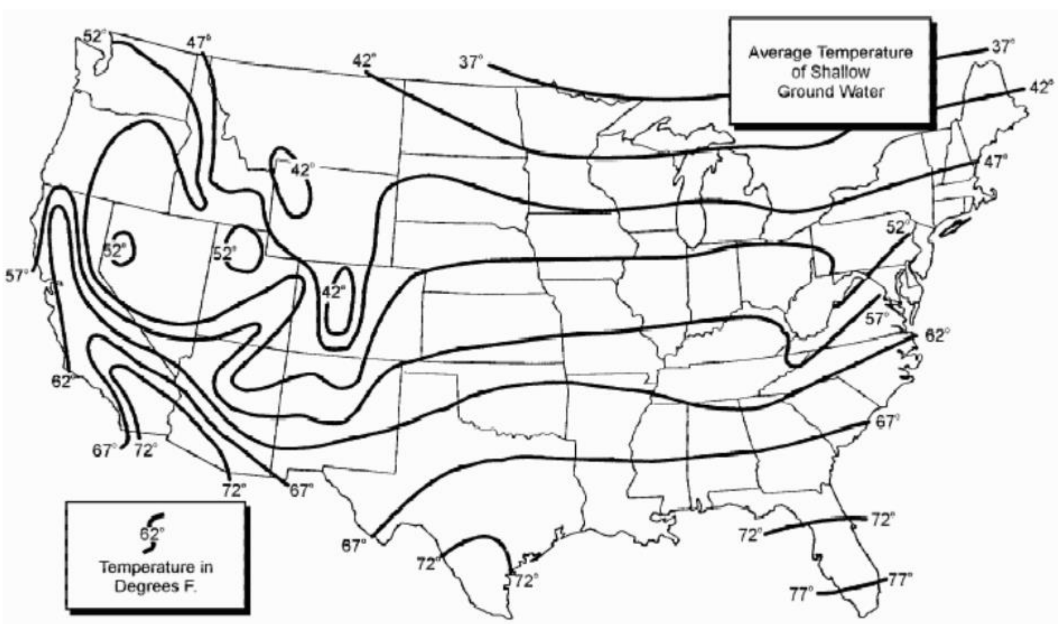


Figure 4-3. Annual Average Shallow Groundwater Temperature in the US (US EPA 2013)

Figures 4-4 (a), (b), and (c) present the temporal variation of temperature at various depths in the landfill for Fairbanks, Des Moines, and Miami, respectively. The modelling results indicate that the waste temperature increases with depth for all three geographic locations. The temperature increased sharply (by approximately 40°C (72°F) at 6 m depth) over the first year and then gradually (3 - 4°C (5 – 7°F) per year) over the subsequent 4 years. The temperature increase during the first year is primarily attributed to the heat released by salt cake. The heat generation from the MSW fraction in the subsequent years resulted in a gradual increase in waste temperature in the landfill in years 2 through 5 for all three geographic locations. A sharp temperature increase during the first year (period of heat release from salt cake) and gradual increase in years 2-5 suggests the significant role the rate of salt cake reactivity has on temperature increase in the landfill. As presented in Figure 4-4, the magnitude of the seasonal variation in temperature decreases with depth for all three geographic locations. The impact of seasonal variation in ambient temperature on the temperature of waste 6 m and below was insignificant for the thermal conductivity and heat capacity used for modeling; a greater waste depth would be influenced by seasonal ambient temperature variations i

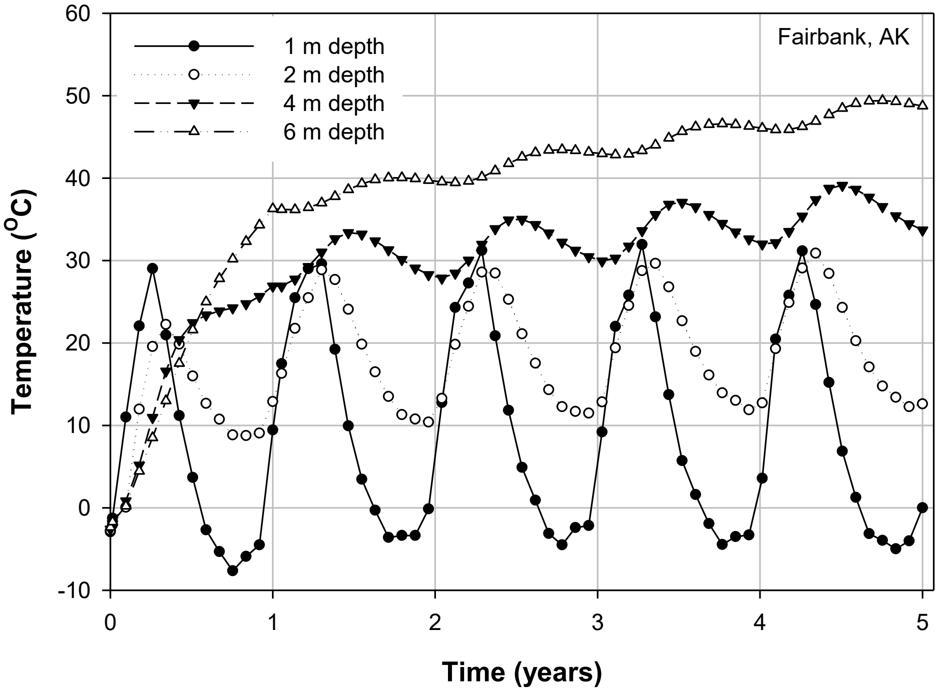


Figure 4-4 (a). Temporal Variation of Waste Temperature at Various Depths for Fairbanks

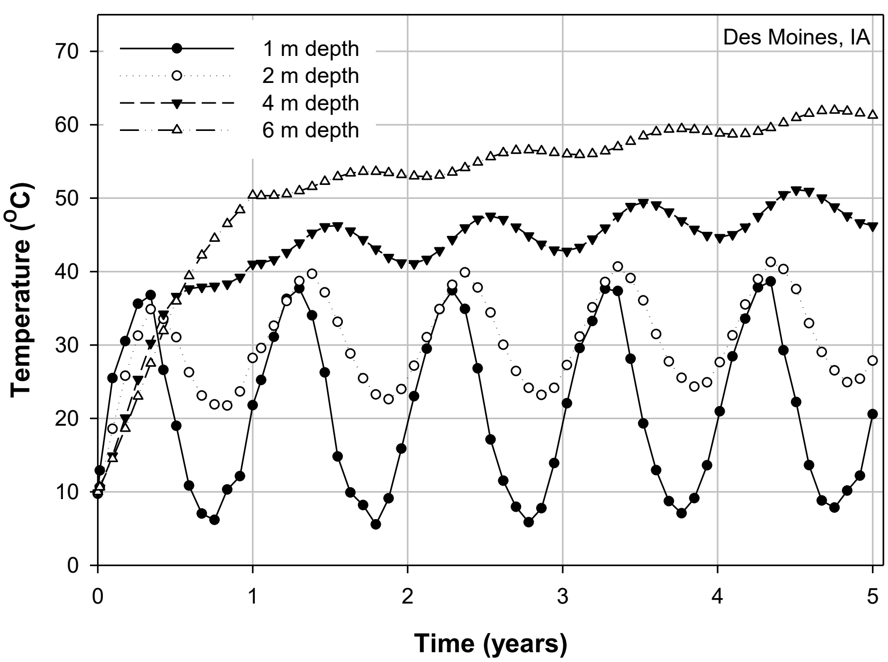


Figure 4-4 (b). Temporal Variation of Waste Temperature at Various Depths for Des Moines

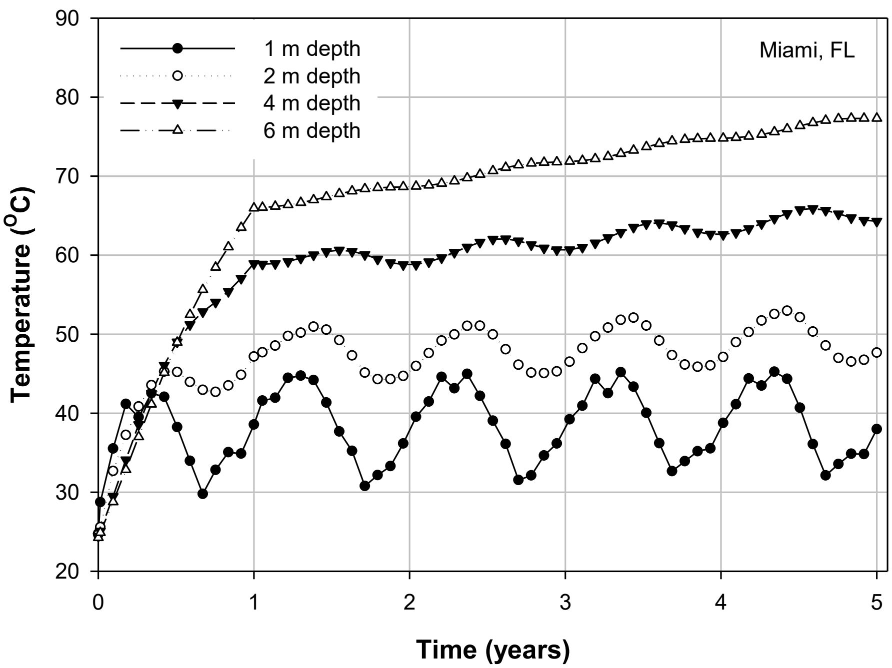


Figure 4-4 (c). Temporal Variation of Waste Temperature at Various Depths for Miami

Figure 4-5 presents the temperature profiles at the end of the first year for three geographic locations. For the same heat generation rate and thermal properties, landfill-received waste temperatures in a colder climate (Alaska) are lower than those in a warmer climate (Miami). The maximum temperature observed in a landfill in Alaska is approximately 25°C (55°F) lower than the maximum observed for a landfill in Miami. It should be noted that the difference in the initial temperature (i.e., temperature before the start of simulations) of these climatic zones is approximately 27°C (48.6°F). To understand the impact of ambient and ground temperatures on the change in the temperature distribution resulting from heat generation, the temperature increase over the initial temperature was plotted at the end of the first year for the three cities.

The heat generated inside the landfill either migrates towards the top or the bottom landfill surface because both surfaces are maintained at a temperature lower than the temperature inside the landfill. The location of the maximum temperature represents the change in direction of heat flow. Heat from the section of the landfill above and below the maximum temperature location migrates upwards (towards the top surface) and downwards (towards the bottom surface), respectively. As can be seen from Figure 4-5, the maximum temperature for Miami occurs slightly above the middle of the landfill suggesting that heat from a greater waste depth is migrating towards the bottom surface of the landfill. This is probably due to the lower temperature of the landfill bottom (22 °C) compared to the average temperature of the top surface (average 24.8 °C)

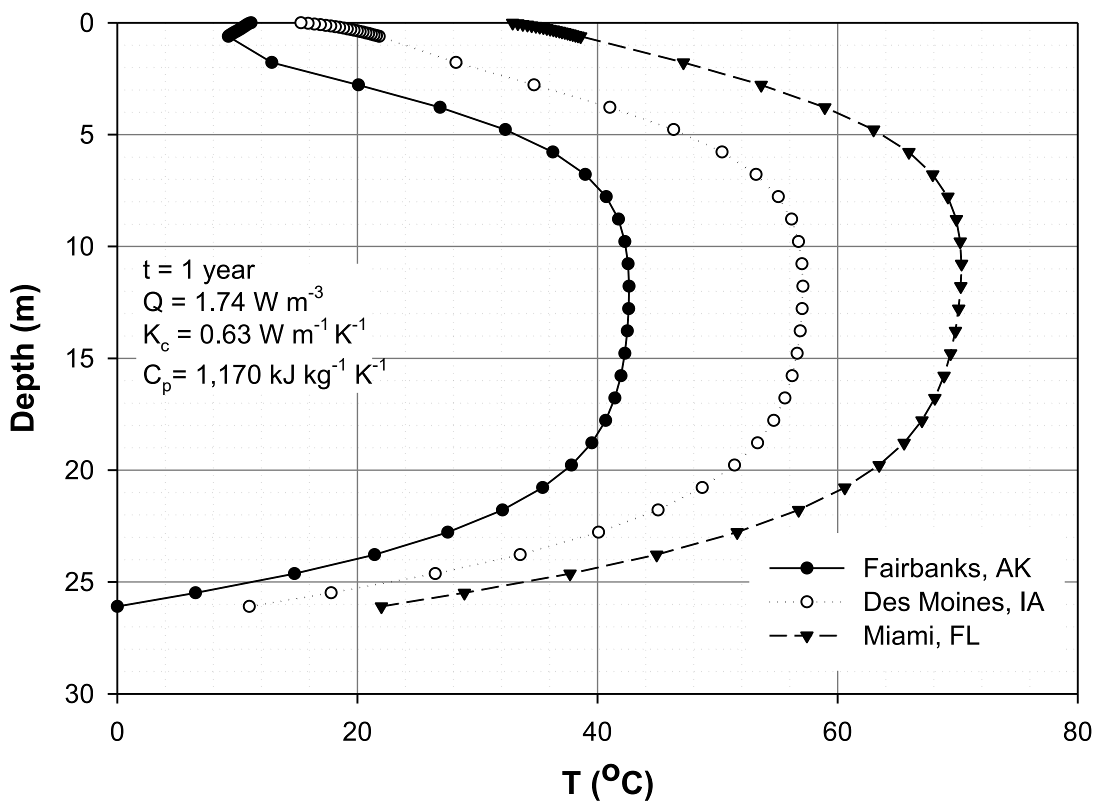


Figure 4-5. Waste Temperature Profile for the Climatic and Subgrade Conditions for Fairbanks, AK, Des Moines, IA and Miami, FL After 1 Year of Placement

Figure 4-6 presents the change in temperature across waste depth for the three cities. The net increase in waste temperature is approximately similar for all three climatic zones, suggesting that the difference in the initial waste temperature at the time of disposal is the primary factor for difference in waste temperature later on; even with a 27°C (48.6°F) and 22°C (71.6°F) temperature difference in ambient temperature and ground, respectively, between Fairbanks and Miami, modeling results show that the temperature change of waste varies less than 3°C (4.8°F) at the end of first year (time corresponding to the maximum waste temperature associated with the salt cake reaction). The results suggest that the variation in climatic conditions across the US (which dictate the initial waste temperature in landfills) would impact the waste temperature by a maximum of 25-30°C (45-54°F); Fairbanks and Miami are assumed to represent the approximate minimum and maximum, respectively, ambient and ground temperature encountered in the US.

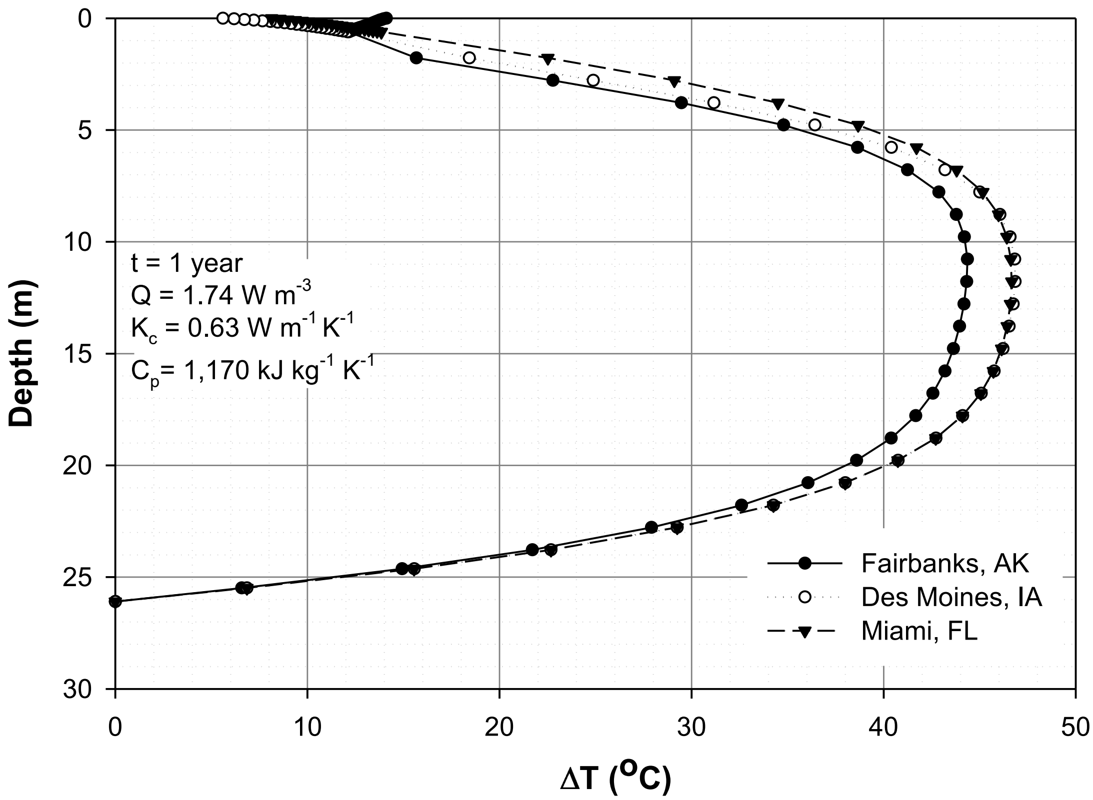


Figure 4-6. Waste Temperature Change Profile for the Climatic and Subgrade Conditions for Fairbanks, AK, Des Moines, IA and Miami, FL After 1 Year of Placement

4.3 Impact of MSW Thermal Conductivity and Heat Capacity on Waste Temperature

As discussed in Section 2.4.3, the thermal conductivity and heat capacity of MSW depends on its composition as well as salt cake content and can vary over a wide range. Simulations were conducted for a series of thermal conductivity and heat capacity values to assess the impact of these waste properties on the temperature distribution in the landfill. The weighted average thermal conductivity and heat capacity were calculated for composite waste (95% MSW and 5% salt cake) using 10th percentile and 90th percentile MSW thermal conductivity and heat capacity values and the value of these properties for salt cake as described in Sections 2.4.2 and 2.4.3 to assess the magnitude of the impact of these properties on the temperature distribution in a landfill.

The upper (using 90th percentile for MSW) and lower (using 10th percentile for MSW) end of the thermal conductivity values of the composite waste were estimated to be 0.32 and 1.23W m^{-1} K^{-1}, respectively. Figure 4-7 shows temperature variation with depth at the landfill center line for three simulations with varying thermal conductivity and a constant heat capacity value. As expected, the temperature is lower for the case with higher thermal conductivity, as higher thermal conductivity promotes greater heat flux. An almost four-fold increase in thermal conductivity from 0.32 to 1.23 W m^{-1} K^{-1} reduces the maximum temperature only slightly from 57 to 55°C (134.6 to 131°F). For the given modeling conditions (heat generation rate and heat capacity), the impact of the MSW thermal conductivity on the maximum temperature is relatively insignificant.

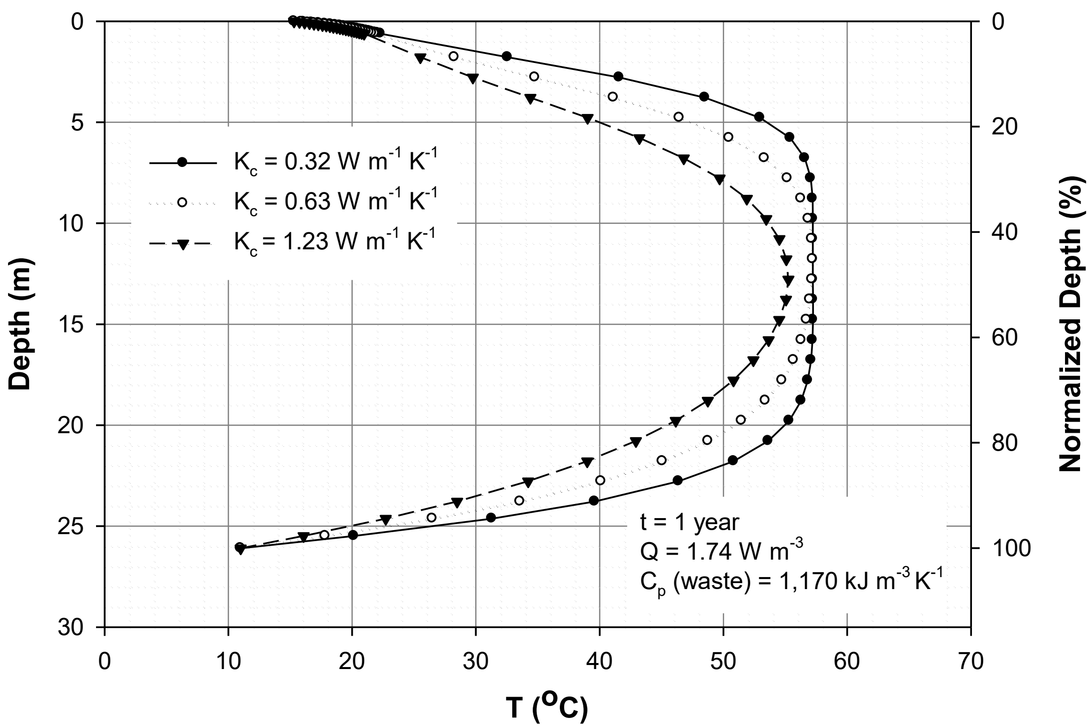


Figure 4-7. Temperature Profiles as a Function of Waste Thermal Conductivity

The upper (using 90th percentile for MSW) and lower (using 10th percentile for MSW) end of the heat capacity value of the composite waste were estimated to be 806 and 1,920 kJ m^{-3} K^{-1}. Figure 4-8 shows temperature variation with depth at the landfill center line for three simulations with varying heat capacity and a constant thermal conductivity value. As expected, the temperature is lower for the case with higher heat capacity, as materials with higher heat capacity can store more heat for a given increase in temperature. An almost 250% increase in heat capacity from 806 to 1,920 kJ m^{-3} K^{-1} reduces the maximum temperature by approximately 50% from 76 to 38°C (168.8 to 100.4°F). For the given modeling conditions (heat generation rate and thermal conductivity), the impact of the MSW volumetric heat capacity on the maximum waste temperature is significant.

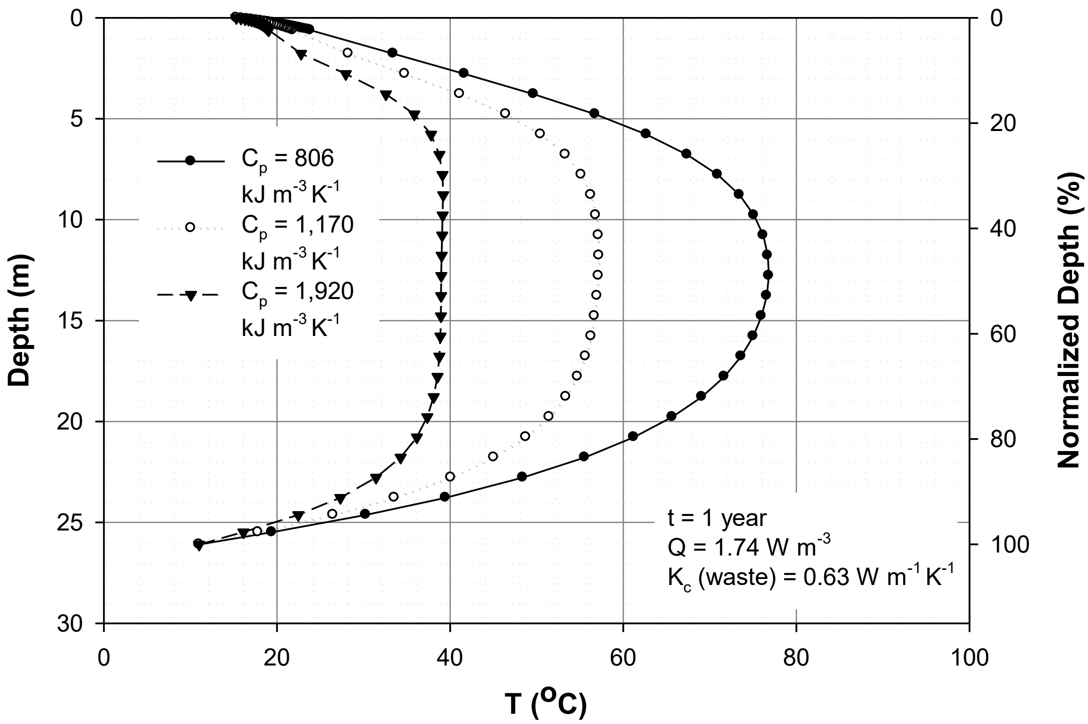


Figure 4-8. Temperature Profiles as a Function of Waste Heat Capacity

Figure 4-9 presents variation of the product of temperature change (ΔT) and volumetric heat capacity (C_p) with depth for these three simulations. This product represents the increase in heat storage of a unit waste volume (cubic meter of waste) associated with the increase in waste temperature. The relatively insignificant variations of $C_p \times \Delta T$ for different C_p values suggests that the change in temperature is approximately inversely proportional to volumetric heat capacity. The results, as expected, suggest that the resultant increase in waste temperature can be reduced by co-disposal with higher heat capacity materials such as water and food waste. However, water and high moisture content waste may also enhance heat release from salt cake.

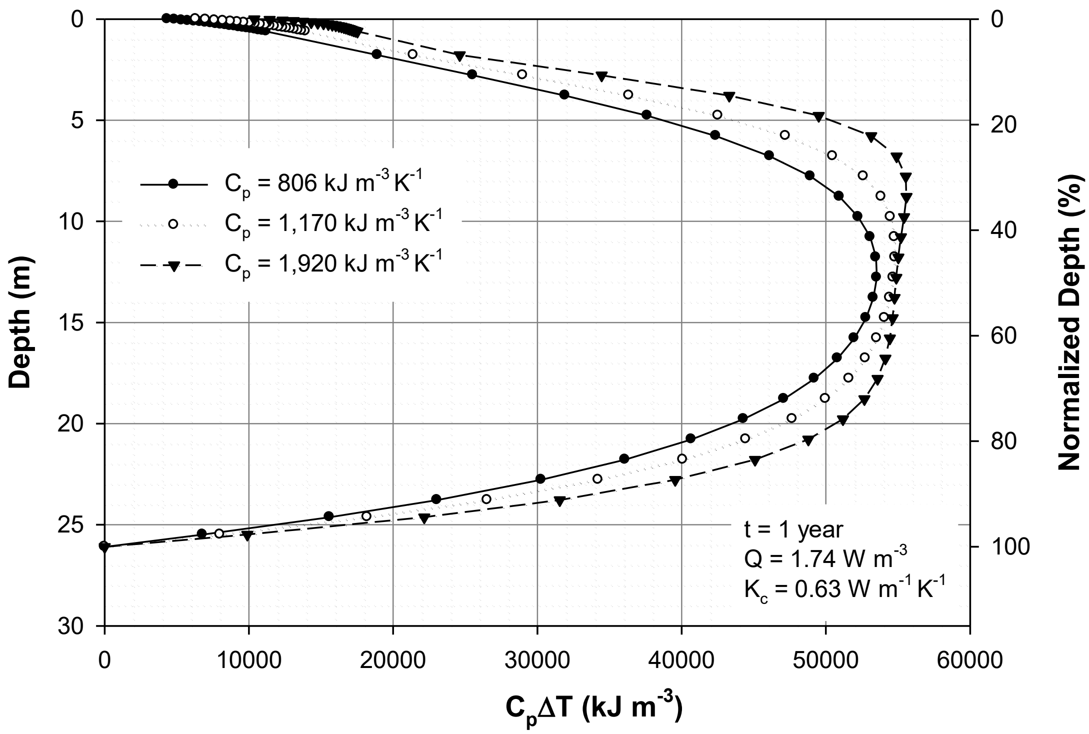


Figure 4-9. $C_p\Delta T$ for Various Waste Heat Capacity Values

4.4 Impact of Moisture Content on Waste Temperature

Upon contact with salt cake, water initiates a heat-releasing reaction resulting in a rise in waste temperature. However, water can also play a significant role in reducing waste temperature due to its significantly higher heat capacity relative to other waste constituents. It was assumed that the heat capacity and thermal conductivity values estimated for composite waste (Sections 2.4.2 and 2.4.3) correspond to a moisture content of 20% (by weight), typical moisture content of landfilled MSW. However, factors such as climatic conditions and operational strategies (dry-tomb operation or operation as bioreactor landfill with addition of external liquid sources) may result in a wide variation of landfill moisture content. Additional simulations were conducted to assess the impact of 10% and 40% (wet-weight basis) moisture content on waste temperature. Although the moisture content would likely influence the rate of both the salt cake and biological reactions and the associated heat generation, the same heat generation rate was used for both (MSW/salt cake and MSW-only) simulations to isolate and analyze the impact of moisture content separately from heat generation.

The weighted-average thermal conductivity and heat capacity of composite waste were calculated based on the values estimated for composite waste (at 20% moisture content) and those of water. The thermal conductivities of composite waste with 10% and 40% moisture content were estimated to be 0.63 and 0.62 W m^{-1} K^{-1}, respectively. The weighted-average heat capacities of composite waste with 10% and 40% moisture content were estimated to be 884 and 1,740 kJ m^{-3} K^{-1}, respectively. The change in moisture content did not impact the thermal conductivity of the waste as the thermal conductivity of the composite waste is approximately equal to that of the water. The volumetric heat capacity significantly changed with moisture content. The temperature profiles for these simulations are presented in Figure 4-10. The temperature profile for the scenario without salt cake is also presented for comparison. The temperature near the landfill surface shows a slight decrease with depth for this case primarily due to the seasonal variation in ambient temperature. The heat generation rate, as for the other simulations, has a much greater influence on waste temperature than the seasonally-varying ambient temperature. As expected, moisture content significantly affected the landfill temperature distribution. Due to the higher heat capacity of wetter waste, the predicted temperature increase was significantly lower.

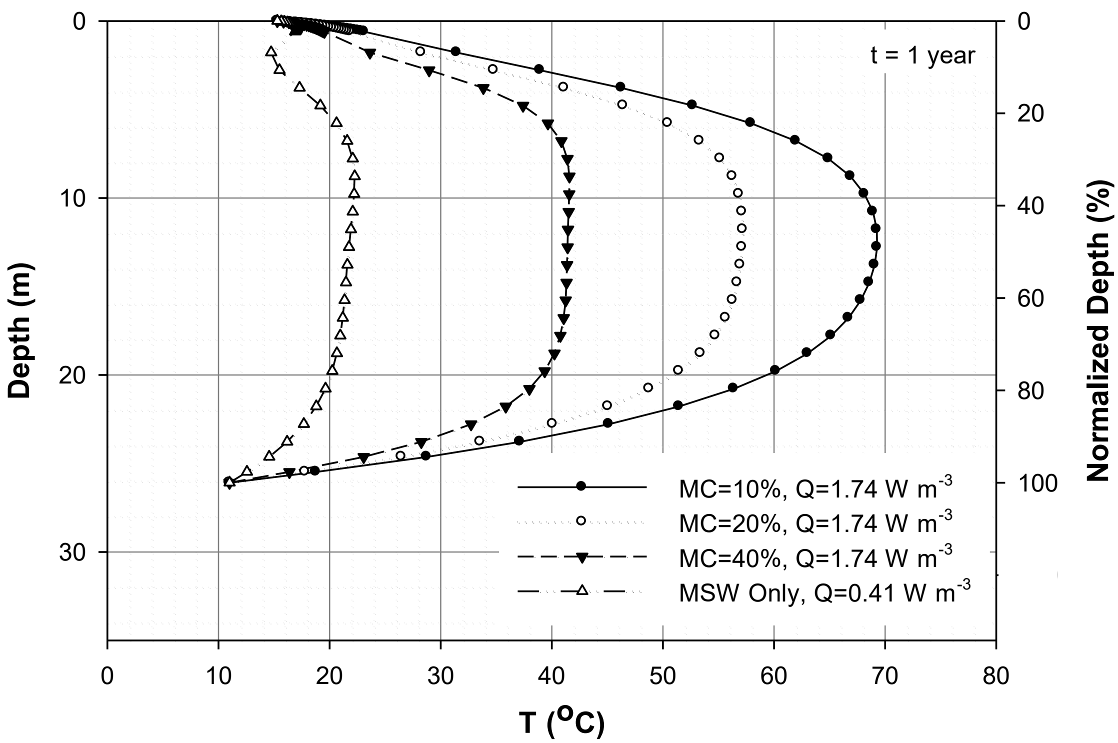


Figure 4-10. Temperature Profile for Various Waste Moisture Contents

4.5 Impact of Heat Generation Rate on Waste Temperature

As discussed in Section 2.4.1, the heat generation rate is dictated by the relative fraction of salt cake in the landfill and the rate of heat release. The heat generation rate used for modeling was based on the assumption that the salt cake releases 100% of its heat within 1 year and salt cake constitutes 5% (by weight) of the total waste deposited in a landfill. Further, it was assumed that salt cake was well mixed with incoming waste and uniformly distributed within the landfill. Factors such as a faster heat release from salt cake and the deposition of salt cake in discrete pockets within the landfill may result in a greater heat generation rate (at least in localized areas around salt cake deposits) than that used for modeling.

Two more simulations (in addition to the base case of 5% salt cake and 95% MSW) were analyzed to assess the impact of heat generation on the temperature profile for Des Moines, IA; of the three locations modeled in the scenarios, Des Moines, IA is the most centrally located in the US and therefore (of the three locations) serves to best approximate continental US climatic conditions. In the first simulation, the heat generation rate was assumed to be 0.41 W m^{-3}, which is the median of the heat generation rate values reported for MSW (i.e. 0% salt cake) in the literature (as presented in Figure 2-2). A heat generation rate of 3.48 W m^{-3} was assumed for the second simulation; this heat generation rate represents a scenario where salt cake comprises 10% (by weight) of the total deposited waste. Figure 4-11 presents the vertical temperature profiles across the center of the landfill for heat generation rates of 0.41, 1.74, and 3.48 W m^{-3}. The maximum temperature increased approximately 33°C (59.4°F) (from 22°C to 55°C [71.6 to 131°F]) between the 0% and 5% salt cake simulations and approximately 50°C (90°F) (from 55°C to 105°C [131 to 221°F]) between the 5% and 10% salt cake simulations. The deviation in the temperature profile shape near the landfill surface for the MSW-only scenario from the other scenarios, as discussed earlier, is attributed to the seasonally-varying ambient temperature. At lower heat generation rates, the seasonally-varying ambient temperature has a stronger influence on the waste temperature near the landfill surface than the heat generation rate. The heat generation rate has a significantly greater impact on the waste temperature than the ambient temperature near the surface for scenarios with greater heat generation rates.

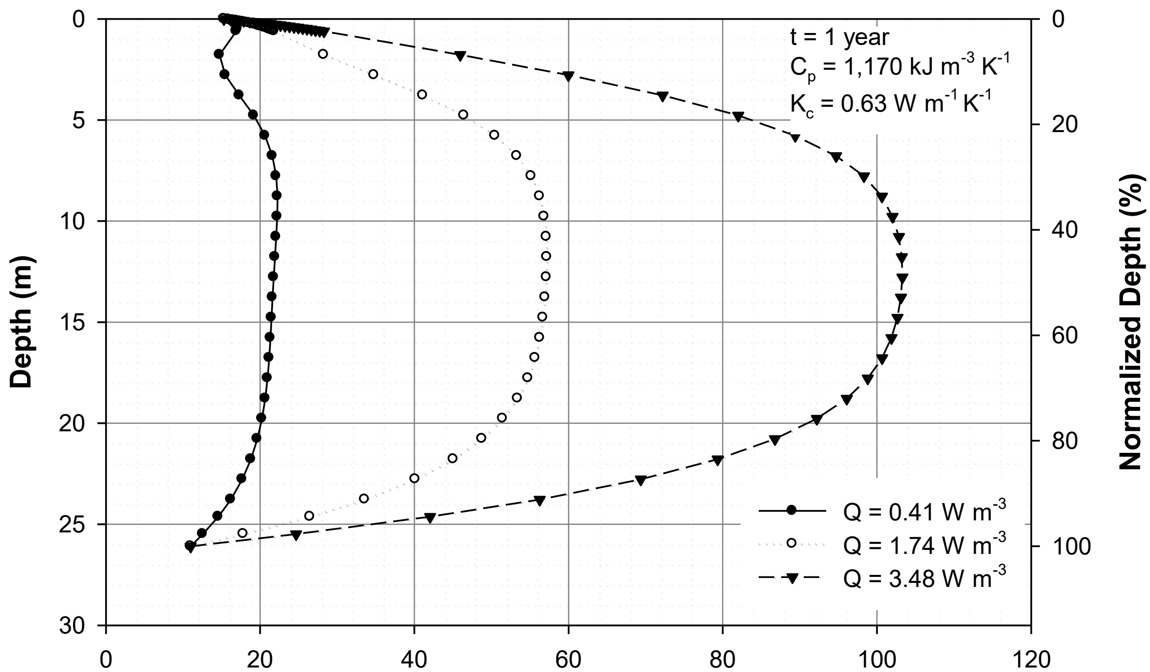


Figure 4-11. Temperature Profiles for Des Moines, IA for Various Heat Generation Rates

Figure 4-12 presents the ratios of temperature change to heat generation rate with depth for heat generation rates of 1.74 to 3.48 W m^{-3}. Overlapping profiles suggest that the temperature increase is directly proportional to the heat generation rate; the deviation for the top half section of the landfill for MSW-only scenario (Q=0.41 W m^{-3}) from the other two profiles is due to stronger influence of seasonally-varying ambient temperature on waste temperature than that of the relatively low MSW heat generation rate. The impact of heat generation rate on waste temperature was found to be similar in magnitude to that of heat capacity; as discussed in Section 4.3, the waste temperature change is approximately inversely proportional to volumetric heat capacity. Depending on salt cake content and heat release timeframe, the heat generation rate can vary over two orders of magnitude (from 0.4 to 40 W m^{-3}), whereas the heat capacity of various MSW constituents has been reported to vary over an order of magnitude (300 - 4,500 kJ m^{-3} K^{-1}). The heat generation rate, therefore, is expected to have the most significant impact on landfill waste temperature of all other parameters.

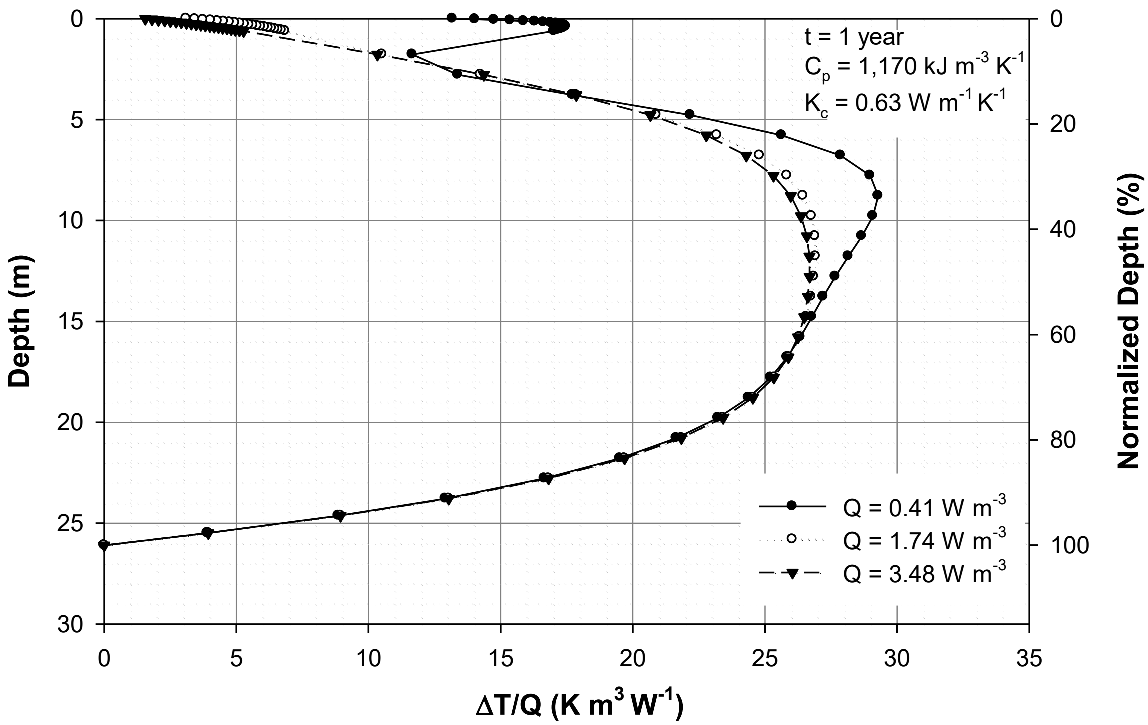


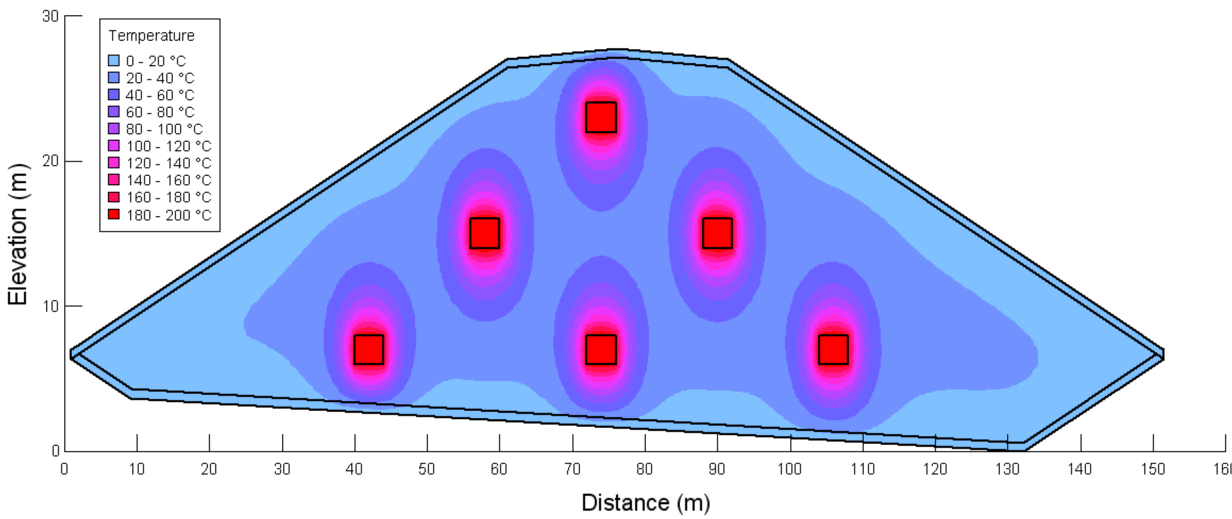
Figure 4-12. Variation of ΔT/Q Ratio with Depth for Des Moines Climatic Conditions for Two Waste Heat Generation Rates

4.6 Impact of Disposal Strategies on Waste Temperature

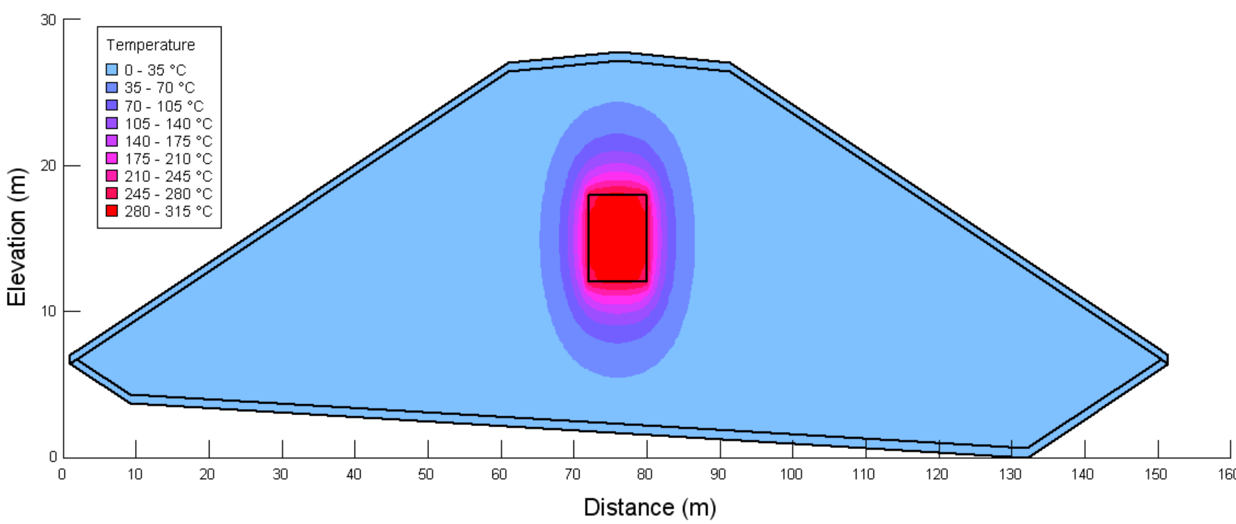
The effect of salt cake placement strategy on waste temperature was analyzed by developing three salt cake placement arrangements where discrete areas of the landfill were assumed to receive pure salt cake deposits (i.e., pockets); previous modeling assumed that salt cake was homogenously mixed in with MSW so that the thermal properties of the landfilled waste were a wet weight-based average of the two materials. In each of the following salt cake pocket arrangements, salt cake waste was assumed to comprise approximately 5% by wet weight (approximately 2% by volume) of the total waste in the landfill. This value was suggested by solid waste industry representatives. Like other simulations, salt cake was assumed to release 100% of its heat over 1 year. The three salt cake placement arrangements modeled are as follows:

1. Salt cake is deposited in discrete areas distributed throughout the entire landfill (referred to herein as *pockets*). The pockets are evenly distributed in the landfill. This scenario simulates the arrangement of salt cake resulting from intermittent salt cake disposal (e.g., once in week or month or quarter).
2. Salt cake is placed as a single "monofill" deposit in the center of the landfill (referred to here as *center*).
3. Salt cake is placed near the top surface (including sideslopes) of the landfill (referred to here as *surface*). The salt cake is placed right below the closure cap in a thin layer over the entire top surface.

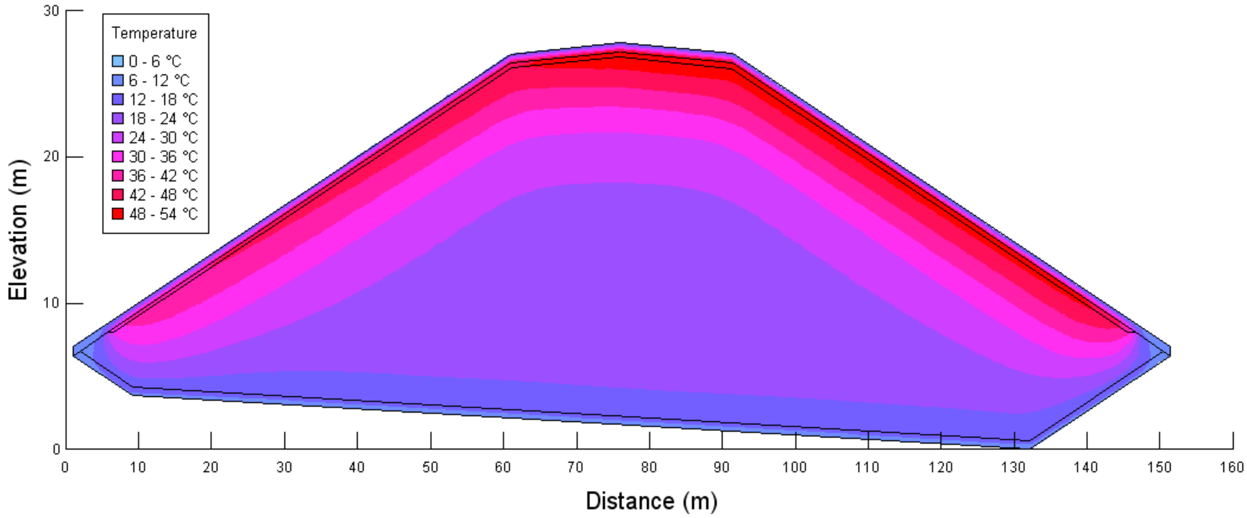
Temperatures reflective of an MSW landfill site in Des Moines, Iowa were used for the landfill top and bottom surfaces. The MSW and salt cake mass was assigned a temperature distribution from the corresponding steady-state simulation (as the temperature at the start the transient thermal analysis time period for each placement scenario. A heat generation rate of 70 W m^{-3}, which represents a rate corresponding to complete heat release within a 1 year (2.74 kJ day^{-1} kg^{-1}), was used for the salt cake in these simulations. A heat generation rate of 0.41 W m^{-3} was used for MSW. Thermal conductivities of 0.375 and 5.5 W m^{-1} K^{-1} were used for MSW and salt cake, respectively. Heat capacities of 1,040 and 6,320 kJ m^{-3} K^{-1} were used for MSW and salt cake, respectively. Figures 4-13 (a), (b), and (c) present the resultant temperature distributions for an MSW landfill where salt cake was deposited in multiple discrete pockets, at the center of the landfill, and over the surface, respectively, at the end of 1 year. As expected, elevated temperatures occurred around salt cake deposits and the temperatures for the pockets and center arrangements are substantially higher than those estimated from when salt cake and MSW were modelled as a homogenous mixture. The temperatures following the surface placement of salt cake are actually slightly lower than the temperatures resulting from homogenously mixed MSW and salt cake (i.e. see Figure 4-1), due to conductive heat loss to the adjacent ambient air.



(a)



(b)



(c)

Figure 4-13. Temperature Distribution within the Landfill Resulting from Salt Cake Deposition in (a) Pockets, (a) Center, and at (c) Surface

Figure 4-14 presents the temperature profile across the landfill center. Salt cake placement in multiple discrete pockets as well as at a single location at the center of the landfill resulted in localized elevated temperatures in the landfill. Salt cake placement in a single location at the center of the landfill resulted in waste temperature of over 290 ºC (554°F); distribution of the same amount of salt cake in six discrete pockets in the landfill resulted in a waste temperature of over 190 ºC (374°F). The placement of salt cake across the surface of the landfill directly underneath the closure cap resulted in the least temperature increase of the placement scenarios modeled.

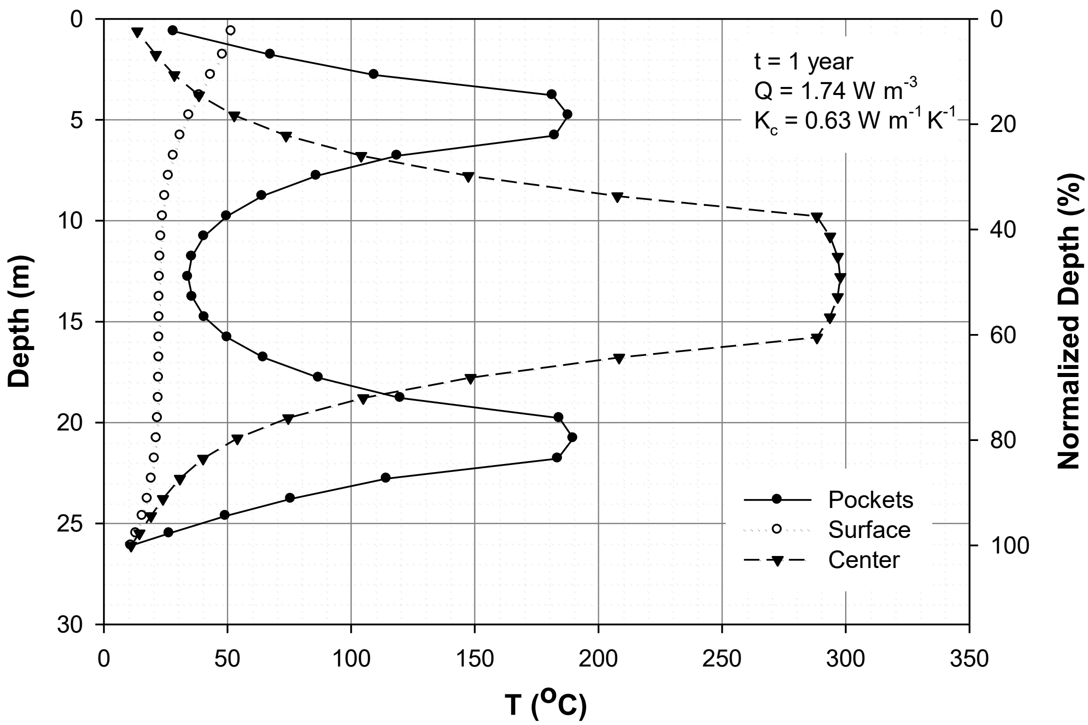


Figure 4-14. Temperature Profile for Various Salt Cake Placement Arrangements

Based on the results of these simulations and the simulation for uniform distribution of salt cake within the landfill, disposal strategy is found to have a significant impact on the temperature distribution in a landfill. More concentrated disposal is expected to result in greater waste temperature. The waste temperatures associated with uniform distribution were much lower than those associated with salt cake placement in discrete pockets. Although a majority of the simulations presented in the report assumed uniform distribution of salt cake throughout the waste, it is expected that salt cake would probably be placed in discrete pockets scattered throughout the landfill due to cost and operational complexities associated with mixing salt cake with MSW to produce a uniformly mixed material before placement in a landfill.

Disposal towards the landfill center is also expected to result in greater a waste temperatures than disposal towards the top surface. Salt cake placement near the exterior landfill surface, where the landfill has approached its permitted elevation or will not be receiving waste for several years, may reduce the impact of salt cake on waste temperature. However, several factors such as the impact on closure cap and side slope stability should be considered for placement near the landfill surface. Elevated temperatures from placing salt cake in the vicinity of the exterior surfaces of the landfill may impact the integrity and performance of the closure cap. Gas constituents released from salt cake deposited near the landfill surface would have greater potential for uncontrolled migration than gas from salt cake deposited in the interior zone of the landfill.

It should be noted that the heat generation rate used for modeling was based on the assumption that all the heat released from the salt cake reaction would occur within one year. However, the entire volume of salt cake, if deposited in large blocks, may not be exposed to moisture until later time periods due to the reduction in salt cake surface area. In this case, the heat release would occur at a lower rate and over a longer duration, which may result in a significantly different temperature distribution than the one presented in Figure 4-14. The peak temperature resulting from the reaction of salt cake and water could potentially occur more than a year after salt cake deposition and the resultant maximum temperature, depending on the modeling conditions, may be lower than that estimated in this section.

Similar to disposal in an MSW landfill, salt cake disposed in dedicated cells would result in elevated temperatures. Elevated temperature even in a cell containing 100% salt cake may have an impact on the containment system integrity and performance would still be a concern. Moreover, constructing dedicated cells for a small waste stream may not be economically feasible. Stabilizing (e.g., by adding water) salt cake prior to its disposal should be considered to mitigate its adverse impact on an MSW landfill. Salt cake, in this case, would be reacted with water at the point of generation or at the landfill to exhaust its heat generation potential in controlled conditions before disposal. Klein et al. (2003) proposed a similar approach for MSW incinerator ash to reduce the risk of liner damage; stabilization by temporarily storing ash for a period prior to disposal in a lined monofill cell was proposed. The potential recovery of heat and gases (previously analyzed by the US EPA (2015) to include approximately 79% hydrogen, 16% methane, and 11% ammonia, by volume) may present additional beneficial opportunities from this approach.

4.7 Impact of Landfill Gas Collection on Waste Temperature

Landfill gas (LFG) and leachate collection may play a role in landfill heat removal, as these fluids are actively extracted from landfills. The convective heat transport with LFG and leachate, therefore, is expected to reduce the waste temperature in landfills. The LFG and leachate flux rate ranges representative of typical landfill conditions were estimated for modeling the impacts of convective heat transport on waste temperature distribution. LFG flux was estimated based on typical gas generation rates and landfill depth ranges. Typical landfill waste depths range from 30 m - 100 m. A gas generation rate range was derived using the default methane production potential (100 m^3 methane per metric ton of MSW), typical LFG composition (50% methane and 50% carbon dioxide, volume basis), the range of decay rate values commonly used for LFG modeling (US EPA 2005) (0.04 - 0.2 $year^{-1}$), a LFG density of 1.23 kg m^{-3}, and a landfilled waste density of 800 kg m^{-3}. For the purposes of a conservative estimate, it was assumed that the entire waste volume was placed instantaneously and the landfill gas generation rate was estimated for time (t=0) immediately following waste placement. For these conditions, LFG generation is estimated to range from of 0.027 - 0.108 kg day^{-1} m^{-3} waste volume. The vertical gravimetric LFG flux rate (U_f) for this generation range and a waste depth range of 30 to 100 m is estimated as 0.1 - 10.8 kg day^{-1} m^{-2} landfill area.

Coupled AIR/W® and TEMP/W® simulations were performed to assess the impact of LFG convection on MSW temperature distribution using the waste thermal properties and heat generation rate presented in Table 3-1. AIR/W® does not allow the specification of different types of gases, so air was used as a surrogate to analyze the effect of LFG convection on the temperature change profile of the MSW waste mass. For simplicity, AIR/W® simulations were conducted for a rectangular waste domain (one-dimensional analysis). AIR/W® does not allow specification of LFG generation rate for the domain modeled. Pressure was specified at the top and the bottom surface such that air would flow vertically from the bottom to the top through the waste to achieve the desired air flux rate, as described above. Furthermore, the model does not allow the specification of the temperaturek of the added air to the materials – the temperature of the added air in this case corresponds to the landfill bottom temperature. The ambient and ground temperatures of Des Moines, IA, were used as the temperature for the top and the bottom of the domain, respectively. In reality, the temperature of the LFG generated in the landfill will be the same as the waste temperature, which is expected to be greater than the air temperature used in these simulations. The simulated air flow, therefore, would result in lower waste temperature as colder air would extract more heat from the surrounding waste than LFG.

Figure 4-15 presents waste temperature profiles across depth for a LFG flux of 0, 0.1, and 11 kg day^{-1} m^{-2} landfill area. Surprisingly, the temperature profiles for all three scenarios were more or less similar. In general, convective heat transport associated with LFG was found to have insignificant impact on the waste temperature distribution for the conditions modeled.

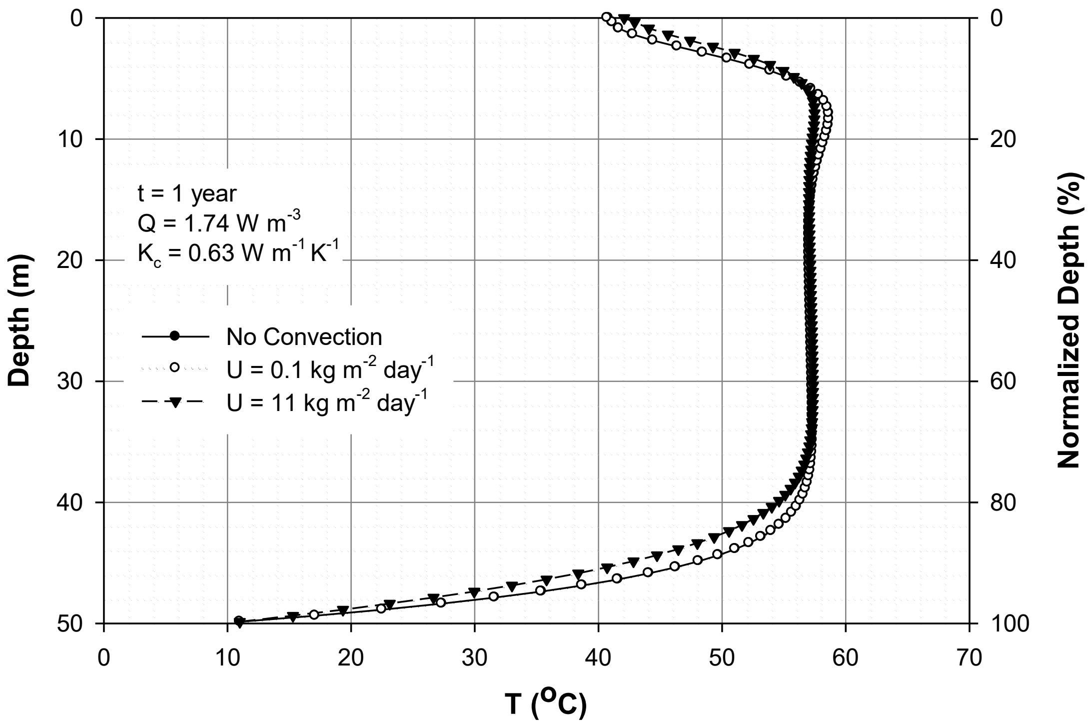


Figure 4-15. Temperature Change vs Depth for Different LFG Flow Rates at the End of One Year

A simplified assessment of the magnitude of the upper end of convective heat transport was conducted based on maximum LFG and leachate flow through landfills to verify the modeling results. A 30-m-deep landfill that accepted 5% salt cake by weight would generate approximately 4,500 kJ day^{-1} of heat per m^2 landfill area; as discussed in Section 2.4.1, the heat generation rate for a landfill accepting 5% (by weight) of salt cake was estimated to be 150 kJ m^{-3} day^{-1}. A conservative (elevated) peak LFG generation rate for a 30-m high landfill following one year of MSW placement is estimated to be 2.65 kg day^{-1} m^{-2}, assuming a typical LFG composition (50% methane and 50% carbon dioxide, volume basis), according to the following equation:

$$\emptyset_{LFG} = 2.74 \times (2kL_o(d \times \rho_{MSW})e^{-kt}) \times \rho_{LFG}$$

Where,

$\emptyset_{LFG}$ = LFG flux (kg day^{-1} m^{-2})
2.74 = conversion factor from Mg year^{-1} to kg day^{-1}
k = MSW decay rate, 0.2 year^{-1}
L_o = MSW methane generation potential, 100 m^3 Mg^{-1}
d = MSW depth, 30 m
ρ_{MSW} = landfilled MSW density, 0.8 Mg m^{-3}
t = year of placement, 1 year

ρ_{LFG} = LFG density, 0.00123 Mg m^{-3}

Using an air-specific heat capacity of 1 kJ kg^{-1} K^{-1} as a proxy for LFG and assuming the temperature of LFG increases by 40°C (72°F) between the time of its generation and its emission from the landfill, the amount of heat convectively transported by LFG is 106 kJ day^{-1} m^{-2} of landfill area, which is less than 3% of the heat generated per day. While convective heat transport is estimated to be insignificant overall, it may play a dominant role in temperature distribution in localized zones such as near gas collection wells due to the convergence of landfill gas flow around gas wells. The localized impact of gas flow on the waste temperature distribution around gas wells was not assessed in the report.

An approximation of the amount of heat transported by leachate was made by assuming 0.5 m of precipitation infiltration per year (20 inches per year or about 1.6 x 10^{-5} cm/s); this amount of infiltration equates to a leachate generation rate of approximately 1,500 gallons per acre per day. An infiltration of 0.5 m year means that more than 30% of the precipitation in an area that receives 1.6 m of rainfall per year (~ 63 inches per year) would infiltrate into the landfill. A majority of rainfall is diverted off the landfill as stormwater run-off due to typical landfill geometry and operating practices in the US. Using a density of 1,000 kg m^{-3}, a specific heat capacity of 4.19 kJ kg^{-1} K^{-1}, and assuming a leachate temperature increase of 40°C (72°F), approximately 230 kJ of heat can be convectively transported by leachate per day, which is approximately 5% of the heat generated per day by a 30-m thick waste layer (with 5% salt cake).

Both the LFG and leachate flux rates estimates presented above are on the higher end of the typical LFG and leachate flow rates from landfills; LFG modeling assumed the first-year's gas generation rate (i.e., which is highest generation rate based on afirst-order decay model) with a high decay rate constant (0.2 $year^{-1}$) and the leachate generation rate assumed 0.5 m (19.7 inches) of annual infiltration. Considering the temperature distribution profile results using these conservative estimates for both landfill gas and leachate flux, convection appears to play a relatively minor role in the overall heat transport within a landfill; convective heat transport appears to be a maximum of 8% of the total heat generation rate. However, this approximation was made assuming uniform gas and leachate flux rates across the entire landfill. Localized leachate and gas flow conditions may have a significantly higher impact on heat transport for discrete landfill areas.

5 Summary and Conclusions

Model simulations were conducted to assess the impact of salt cake disposal on temperature in an MSW landfill. A series of simulations was conducted to assess the impact of thermal properties of waste (heat capacity and thermal conductivity), heat generation rate, moisture content, climatic conditions (ambient and ground temperature), and salt cake placement configuration on the landfill temperature profile. Overall, the thermal conductivity of the MSW and convective heat transport were found to have a minor impact on the temperature of an MSW landfill that receives unreacted salt cake. Likewise, the ambient and ground temperatures were found to have a minor impact on the net increase in waste temperature over the initial temperature. However, due to the dependence of the initial waste temperature on climatic conditions, the final landfill temperatures resulting from salt cake disposal were found to be moderately impacted by climatic conditions; given the same landfill geometry, the maximum temperature difference at a given depth is expected to be 30°C (54°F) across the US (between a landfill located in Miami versus a landfill located in Fairbanks).

The waste heat capacity and heat generation rate were found to have significant impact on changes in waste temperature. An approximate 200% increase in heat capacity was found to correspond to an approximate 50% reduction in the waste temperature change over the course of 1 year. A 100% increase in heat generation rate was found to double the increase in waste temperature over the course of 1 year. The heat generation rate, which is dictated by the amount of salt cake relative to MSW and the timeframe of heat release from salt cake, is estimated to vary over two orders of magnitude, whereas the heat capacity is estimated to vary over an order of magnitude. Due to a much wider range, the heat generation rate is expected to have the greatest impact on the landfill temperature of all the parameters analyzed. A review of the literature suggested a scarcity of information on reliable waste thermal properties and heat generation rates. Future research should focus on quantifying these properties for MSW and salt cake.

The simulation results presented in this report suggest that salt cake and its placement play a significant role on waste temperatures in a landfill. Salt cake deposited uniformly throughout the landfill or applied in a thin layer near the landfill surface were found to have the least impact on the landfill temperature of the different salt cake disposal strategies modeled (which also included discrete pocket placement and a single central monofill deposit). The placement of salt cake in a single location at the center of a landfill resulted in waste temperatures as high as 290°C (554°F). Placement in multiple pockets scattered throughout the landfill resulted in waste temperatures as high as 190°C (374°F).

Previous research shows that the bulk of salt cake waste reactions occur when the material is exposed to water and that the reactions proceed quickly and may be expected to be completed within a short time. Therefore, stabilizing the salt cake (i.e., completely reacting it with water) before placing it in an MSW landfill may be a more viable management approach than current techniques for controlling temperature increases in landfills. This approach could lead to opportunities to beneficially recover the heat and combustible gas generated during salt cake waste reactions while mitigating the unintended consequences to landfill infrastructure and human health and safety that may occur if the unreacted salt cake was placed in an MSW landfill. Additional challenges associated with stabilization outside of the landfill would include excess water (i.e., contact water from the stabilization reaction) management and maintaining the integrity of the liner, gas and excess water collection and control system infrastructure.

The major limitations of the analysis presented in the report are as follows:

1. The actual heat generation rate of salt cake deposited in an MSW environment is unknown. While previous research has estimated total heat release from the salt cake, the timeframe of the reaction which occurs following placement in an MSW landfill is dependent on a number of factors (e.g., particle size of the salt cake, localized moisture conditions). In addition, a constant heat generation

rate from MSW and salt cake was assumed. In reality the heat generation associated with biological decomposition is expected to vary over time. Also, different areas of MSW waste will decompose differently, depending on the age and composition of the deposited waste. The localized heat generation from biological activity as well as from the salt cake may result in significantly greater waste temperatures than simulated in this study.

2. It was assumed that salt cake represents 5% (by weight) of the waste mass. As discussed in Section 4.5, the salt cake content has a significant impact on waste temperatures. Site-specific modeling efforts should consider using heat generation rate that is reflective of salt cake content of the site.
3. The landfill bottom surface (i.e., the base of the liner) was assumed to be maintained at a constant temperature throughout the simulation duration. As a result, this boundary acted as a "sink" for the heat migrating towards this boundary for all the simulations. If the heat is not effectively removed by the soil beneath the bottom surface, heat generation within the landfill may result in an increase in the liner temperature. Due to the nature of the boundary condition used for the landfill bottom, the results presented in the report should not be used to evaluate the impact of elevated temperature on the liner system.
4. The heat release from salt cake was assumed to occur once the landfill is completely filled. In reality, heat generation from the salt cake may start as soon as it is placed in the landfill and a significant fraction of its heat generation potential may be exhausted due to exposure to precipitation and the associated surface runoff before it is covered with more waste. As suggested by the surface placement scenario (Section 4.6), the waste temperature developed in this case would be lower than those associated with modeled cases where heat generation is assumed to begin after the salt cake is covered with layer(s) of waste insulating it from the ambient environment.
5. The convective heat transport analysis assumed uniform liquid and gas flux through the waste. The landfill liquid and gas movement, however, may vary significantly throughout the landfill. The localized contribution of convective cooling is expected to be concomitant with liquid or gas flow rates. The convection mode of heat transport may play a significantly greater role in heat transport on a localized scale than simulated in this study.
6. The impact of landfill size (e.g., waste depth and area) on temperature distribution was not evaluated. A greater waste depth is expected to impede heat removal from the landfill interior and may result in waste temperatures greater than those simulated in this study.

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7 Appendix A – Thermal Properties Used in Modeling

Table A-1. Summary of Heat Generation and Transport Parameters Reported in Peer-Reviewed Literature

Source	Specific Heat Capacity (J kg^{-1} K^{-1})	Thermal Conductivity (W m^{-1} K^{-1})	Density (kg m^{-3})	Heat Generation rate[1]	Flow Rate/Gas Produced
El- Fadel et al. (1996):	-	-	688 - 755 [j]	3163 kJ per kg cellulose [m]	59,511 – 187,035 (m^3 $year^{-1}$) [q]
Gholamifard (2008)	Site 1: 1,000 – 1,100 Site 2: 900 [a]	Site 1: 0.8 Ste 2: 1 [g]	-	-	53 kg gas per ton MSW (in 10 years) [u]
Hanson et al. (2008) Hanson et al. (2013)	MI: 2,000 NM: 1,589 AK: 1,883 BC: 2,200 [b]	MI: 1 NM: 0.6 AK: 0.3 BC: 1.5 [e,f]	[k] MI: 1,000 NM: 755 AK: 531 BC: 1,000	[n] MI: 32.8 AK: 6.91 (kJ day^{-1} m^{-3})	-
Hanson et al. (2000)	2,000 [e]	1 [e,f]	1,000 [k]	100.2 - 131.3 [w] (kJ day^{-1} m^{-3})	
Meima et al. (2008)	860 – 1,260 [e,f]	-		-	-
Nastev et al. (2001)	[e] 1,331	[i] Wet: 0.184 Dry: 0.038	760 [e]	40.2 kJ per mol of CH_4 and CO_2 produced [p]	94.6 m^3 CH4 per MT MSW (assuming CH4=55% and CO2 = 45% (v/v)) [r]
Neusinger et al. (2005)	-	1 [c]	-	-	-
Rowe et al. (2010)	1,940 – 2,360 [d]	0.35 - 0.96 [d]	-	37.7 - 403.5 (kJ day^{-1} m^{-3}) [d]	-
Thomas et al. (1999)	600 [e]	0.5 [e]	1600 [e]		-
Yesiller et al. (2005)	2,000 kJ m^{-3} K^{-1} [e,f]	1 [c]	-	23 - 77 MJ m^{-3} [t]	MI: 1.23 NM: 0 AK: 0.80 BC: 2.18 (m^3 $year^{-1}$) [s]
Lefebvre et al. (2000)	600 kJ m^{-3} K^{-1}	0.1 [f]	545 - 862 [f]	460 kJ per mol O_2 [f]	260 (m^3 $hour^{-1}$) [f]
Pirt (1978)	-	-	-	0.377 kJ per kg glucose [m]	-
Tchobanoglous (1993)	-	-	-	5450 kJ per kg waste [x]	-
Zanetti (1997)	-	-	-	180 MJ m^{-3} [y]	-

MI = Michigan; NM = New Mexico; AK = Alaska; BC = British Columbia

Additional Notes:

1. Units as presented in literature
a. Estimated for study and falls within the range proposed by other authors (Meima et al. 2007)
b. Calculated based the volumetric heat capacities of individual component of the material (MSW) on a volumetric basis. Converted to mass basis using provided densities.
c. Author assumed the value.

d. Adopted literature-reported MSW thermal property that varies based on the MSW layer (exposed to air, leachate or neither).
e. Adopted from literature-reported values.
f. Based on experimental data.
g. Used numerical simulations to derive; however, values were also based on previous studies done: Aran (2000), Yessiler et al. (2005).
h. Determined using laboratory and field thermal conductivity probe experiments as well as using some literature data.
i. Assumed values from (Oweis and Khera 1990; Schroeder et al. 1994; Reitsma and Kueper 1994; Luckner and Schestakow 1991.)
j. Densities were based on six cells that were designed for the experiment.
k. Based on operational site records.
l. Based on in-situ measurements in a real landfill using governing equations. Assumes heat diffusivity is constant. Originally given in units of [W/m^3], but converted to $kJ/d\text{-}m^3$.
m. Based on enthalpy reactions for anaerobic pathway reactions or some other theoretical analysis of the biochemical decomposition of waste.
n. Based on mathematical modeling, field data, and literature reported data.
o. Estimated using simulation. Assumed to be the heating rate of ash stored for 3-6 weeks.
p. Based on the relationship for anaerobic biodegradation of glucose (Pirt, 1978)
q. Based on measured total LFG production produced over 4 years.
r. Based on the total gas recovery rates in 1 year
s. NM and AK did not have a gas collection system. AK was estimated based on numerical modeling.
t. Estimated based on field data.
u. Estimated over 10 years and based on a numerical simulation. It does not consider aerobic/acidogenic phases).
v. Based on C:N ratios for organic matter.
w. Used temperature-dependent exponential decay formulation for heat generation from two cells (one which took MSW, the other a mix of C&D and MSW). These values represent the peak heat generation rates.
x. Calculated based on the US EPA reported MSW composition, density of waste = 1,000 kg m^{-3}, and molecular fractions.
y. Calculated using ideal gas law: density of waste = 1,000 kg m^{-3}, gas generation capacity = 200 m^3 gas per m^3 waste, methane content of gas = 60%.

Table A-2. List of Simulation Conducted for the Analysis presented in this Report

Simulation ID	Condition/Parameter	Heat Capacity (kJ m^{-3} K^{-1})	Thermal Conductivity (W m^{-1} K^{-1})	Heat Generation (W m^{-3})	Convection (kg m^{-2} day^{-1})	Figure
1	Contained	1170 (waste), 3500 (containment layers)	0.63 (waste), 0.70 (containment layers)	1.74	0	4-2
2	Uncontained	1170 (waste and containment layers)	0.63 (waste and containment layers)	1.74	0	4-2
3	Seasonal Temperature Variation - AK	1170	0.63	1.74	0	4-4 (a)
4	Seasonal Temperature Variation - IA	1170	0.63	1.74	0	4-4 (b)
5	Seasonal Temperature Variation - FL	1170	0.63	1.74	0	4-4 (c)
6	Climate and Ground Temperature - AK	1170	0.63	1.74	0	4-5, 4-6
2	Climate and Ground Temperature - IA	1170	0.63	1.74	0	4-5, 4-6
7	Climate and Ground Temperature - FL	1170	0.63	1.74	0	4-5, 4-6
8	Thermal Conductivity	1170	0.32	1.74	0	4-7
2		1170	0.63	1.74	0	4-7
9		1170	1.23	1.74	0	4-7
10	Heat Capacity	806	0.63	1.74	0	4-8, 4-9
2		1170	0.63	1.74	0	4-8, 4-9
11		1920	0.63	1.74	0	4-8, 4-9
12	Moisture Content – MSW Only	1170	0.63	0.41	0	4-10
13	Moisture Content - 10%	884	0.62	1.74	0	4-10
2	Moisture Content - 20%	1170	0.63	1.74	0	4-10
14	Moisture Content - 40%	1740	0.63	1.74	0	4-10
12	Heat Generation Rate - MSW Only	1170	0.63	0.41	0	4-11, 4-12
2	Heat Generation Rate - 5% SAP	1170	0.63	1.74	0	4-11, 4-12
15	Heat Generation Rate - 10% SAP	1170	0.63	3.48	0	4-11, 4-12
16	Salt Cake Placement Arrangement - Pockets	MSW: 1040 SAP: 6320	MSW: 0.375 SAP: 5.5	MSW: 0.41 SAP: 70	0	4-14
17	Salt Cake Placement Arrangement - Surface	MSW: 1040 SAP: 6320	MSW: 0.375 SAP: 5.5	MSW: 0.41 SAP: 70	0	4-14
18	Salt Cake Placement Arrangement - Center	MSW: 1040 SAP: 6320	MSW: 0.375 SAP: 5.5	MSW: 0.41 SAP: 70	0	4-14
19	Convection	1170	0.63	1.74	0	4-15
20	Convection	1170	0.63	1.74	0.1	4-15
21	Convection	1170	0.63	1.74	11	4-15