

# CHARACTERIZING SPONTANEOUS FIRES IN LANDFILLS

by

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## ABSTRACT

Landfill fires are relatively common incidents that landfill operators encounter which have great impact on landfill structure and the environment. According to a U.S. Fire Administration report in 2001, an average of 8,300 landfill fires occurs each year in the United States, most of them in the spring and summer months. Subsurface spontaneous fires are considered the most dangerous and difficult to detect and extinguish among landfill fires. Few studies have been conducted on spontaneous fires in landfills. Information regarding the thermal behavior of solid waste is not available nor have measurements been made to evaluate spontaneous ignition of solid waste. The purpose of this research was to provide information concerning the initiation of spontaneous ignition incidents in landfills, and investigate the conditions favoring their occurrence.

This study enabled better understanding of the self-heating process and spontaneous combustion in landfills. Effects of parameters critical to landfill operation on spontaneous combustion were determined. Spontaneous combustion occurs when materials are heated beyond the ignition temperature. Temperature rise occurs inside the landfill due to exothermic reactions which cause self-heating of the solid waste. Oxygen introduction leading to biological waste degradation and chemical oxidation is believed to be the main cause of rising solid waste temperatures to the point of ignition.

A survey was distributed to landfill operators collecting information regarding spontaneous fires incidents in their landfills. Survey results raised new questions necessitating further study of subsurface fires incidents. Subsurface spontaneous fires were not restricted to any landfill geometry or type of waste (municipal, industrial, commercial, and construction and demolition).

Results showed that landfill fires occur in landfills that do and do not recirculate leachate. Although new methods have been developed to detect subsurface fires, landfill operators depend primarily on visual observation of smoke or steam to detect the subsurface fires. Also, survey results indicated that excavating and covering with soil are the most widespread methods for extinguishing subsurface fires.

Methane often has been suspected for initiating spontaneous subsurface fires in the landfill. However, combustible mixture of methane and oxygen requires very high temperature to ignite. In this study it was shown that spontaneous fires are initiated by solid materials with lower ignition points. Laboratory tests were conducted evaluating the effect of moisture content, oxygen concentration and leachate on spontaneous ignition of solid waste. A new procedure for testing spontaneous ignition is described based on the crossing-point method. The procedure was used to study the spontaneous combustion of solid waste and determine the auto-ignition temperature of the solid waste components and a synthesized solid waste. Correlations have been established between auto-ignition temperature, specific weight and energy content and between self-heating temperature and specific weight. Correlations indicated that compaction can help avoid spontaneous combustion in the landfill. Dense materials require higher energy to increase in temperature and limit the accessibility of oxygen.

In the experimental work, moisture was found to promote both biological and chemical self-heating. Increasing moisture content lowers the solid waste permeability and absorbs more energy as it evaporates. Dissolved solids in leachate were found to promote self-heating and ignition more than distilled water. Varying oxygen concentrations indicated that heat generation

occurs due to chemical oxidation even at oxygen concentration as low as 10% by volume. However, at 10% by volume oxygen, solid waste did not exhibit thermal runaway nor flammable combustion. At 0% by volume oxygen, tests results indicated occurrence of self-heating due to slow pyrolysis.

A numerical one-dimensional energy model was created to simulate temperature rise in landfill for four different scenarios. Using the results from the laboratory experiment, the model estimated the heat generation in solid waste due to chemical reactions. Results from the scenario simulations indicated that moisture evaporation is the major heat sink in the landfill. The model showed that gas flow has a cooling effect due to increasing amount of evaporated water and can control the temperature inside the landfill. The model showed that a temperature higher than the biological limit can be maintained in the landfill without initiating spontaneous fire.

This work is dedicated to my family with love.

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## TABLE OF CONTENTS

LIST OF FIGURES .....	XI
LIST OF TABLES.....	XII
CHAPTER ONE INTRODUCTION.....	1
Background Information .....	1
Research Scope and Objectives .....	3
Dissertation Organization.....	4
References .....	5
CHAPTER TWO BACKGROUND INFORMATION.....	7
Case Studies .....	7
Shale Spoils Fire in Dallas, Texas .....	7
Bandung Dumpsite Failure in Indonesia.....	8
Composting Facility Fire in Huron, Ohio .....	9
Pilot Composting Facility at Albuquerque, New Mexico .....	10
Delta Shake and Shingle Landfill Fire, North Delta Canada .....	10
Vancouver Landfill Fire in Vancouver, Canada .....	11
Combustion .....	12
Premixed Combustion.....	14
Diffusion Combustion.....	15
Ignition and Propagation .....	16
Biological Self Heating .....	18
Chemical Self-Heating.....	20
Chemical Oxidation .....	20
Pyrolysis .....	23
Heat Loss .....	24
Air Intrusion .....	25
Moisture.....	26
References .....	28
CHAPTER THREE SPONTANEOUS COMBUSTION FIRES IN MSW LANDFILLS.....	35

<b>Background Information .....</b>	<b>35</b>
<b>Methodology.....</b>	<b>38</b>
Questionnaire .....	38
<b>Results and Discussion .....</b>	<b>39</b>
Responses .....	39
Events Prior to Fire .....	39
Detection Methods .....	40
Extinguishing Methods .....	41
Events During the Fire .....	44
<b>Conclusions .....</b>	<b>45</b>
<b>References .....</b>	<b>46</b>
CHAPTER FOUR FACTORS INFLUENCING THE SPONTANEOUS COMBUSTION IN LANDFILLS .....	
48	
<b>Background.....</b>	<b>48</b>
<b>Materials and Methods .....</b>	<b>51</b>
Equipment.....	51
Material.....	51
Methodology.....	52
<b>Results and discussion.....</b>	<b>56</b>
Temperature profile .....	56
Solid Waste Components .....	58
Effect of Moisture Content on Spontaneous Combustion.....	61
Effect of Leachate on Spontaneous Combustion .....	69
Oxygen concentration .....	70
<b>Conclusions .....</b>	<b>73</b>
<b>References .....</b>	<b>74</b>
CHAPTER FIVE ENERGY MODELING OF THE SPONTANEOUS COMBUSTION .....	
77	
<b>Introduction .....</b>	<b>77</b>
<b>Model Description.....</b>	<b>77</b>
<b>Estimation of Chemical Oxidation Kinetic Parameters .....</b>	<b>82</b>
<b>Gas Flow Rate Effect.....</b>	<b>85</b>
<b>Simulation Scenarios .....</b>	<b>88</b>
Scenario 1: Anaerobic Degradation .....	88
Scenario 2: Aerobic Degradation .....	89
Scenario 3: Spontaneous Combustion.....	89
Scenario 4: Reactive Solid Waste .....	91

<b>Conclusions .....</b>	<b>92</b>
<b>References .....</b>	<b>92</b>
<b>CHAPETR SIX CONCLUSIONS AND RECOMMENDATION .....</b>	<b>94</b>
<b>Conclusions .....</b>	<b>94</b>
<b>Recommendations.....</b>	<b>96</b>
<b>APPENDIX A: SURVEY QUESTIONNAIRE.....</b>	<b>98</b>

## LIST OF FIGURES

Figure 3.1: Events Prior to Fire.....	40
Figure 3.2: Fire Detection Methods .....	41
Figure 3.3: Fire Extinguishing Methods .....	43
Figure 3.4: Fire Extinguishing Period.....	43
Figure 3.5: Events During the Fire .....	44
Figure 4.1: Experimental System Setup.....	54
Figure 4.2: Typical Temperature Profiles and Characteristics Points .....	58
Figure 4.3: Graphical presentation of AIT (in °C) under different moisture and leachate content .....	65
Figure 4.4: Graphical presentation of $T_{S-H}$ (in °C) under different moisture and leachate content .....	66
Figure 4.5: Graphical presentation of $C_{ig}$ (in °C) under different moisture and leachate content .....	66
Figure 4.6: Graphical presentation of $S_{ig}$ (in °C) under different moisture and leachate content .....	67
Figure 4.7: Cumulative Distribution of Wet Samples (all liquid contents) for AIT (in °K) compared to Dry Samples.....	67
Figure 4.8: Cumulative Distribution of Wet Samples (all liquid contents) for $T_{S-H}$ (in °K) compared to Dry Samples.....	68
Figure 4.9: Cumulative Distribution of Wet Samples (all liquid contents) for $C_{ig}$ (in °K) compared to Dry Samples.....	68
Figure 4.10: Cumulative Distribution of Wet Samples (all liquid contents) for $S_{ig}$ (in °K) compared to Dry Samples.....	69
Figure 5.1: Simulated Section Diagram.....	79
Figure 5.2: Diagram of Experiment Simulation .....	84
Figure 5.3: Laboratory experiment simulation for dry MSW in air .....	86
Figure 5.4: Temperature profile of simulated section at different gas flow rates.....	86
Figure 5.5: Profile of Energy Balance Equation Components in Aerobic Condition.....	88
Figure 5.6: Temperature profiles of modeled landfill scenarios.....	91

## LIST OF TABLES

Table 4.1: Solid waste components preparation, as received energy content and test observations .....	55
Table 4.2: Leachate constituent data (From Orange County Landfill).....	56
Table 4.3: Dry solid waste components in saturated air <sup>a</sup> .....	63
Table 4.4: Results for AIT under different moisture and leachate content <sup>a</sup> .....	63
Table 4.5: Results for $T_{S-H}$ under different moisture and leachate content <sup>a</sup> .....	64
Table 4.6: Results for $C_{ig}$ under different moisture and leachate contents <sup>a</sup> .....	64
Table 4.7: Results for $S_{ig}$ under different moisture and leachate contents <sup>a</sup> .....	65
Table 4.8: Characteristic Temperature for dry solid waste at 10% Oxygen.....	72
Table 4.9: Characteristic temperatures for dry solid waste at 0% oxygen.....	72
Table 5.1: Values for solid waste parameters used in model.....	87

## CHAPTER ONE INTRODUCTION

### **Background Information**

The municipal solid waste landfill is often found to be the most economical and environmentally friendly solution for disposal of solid waste. However, because of the nature of the landfill, full control of the internal processes has not yet been achieved. Landfills are complex systems that promote various interrelated biological and chemical reactions. These reactions are sequential and often lead to processes or incidents that affect the landfill structure or the surrounding environment.

Landfill fires are relatively common incidents or problems that landfill operators encounter and have a great impact on the landfill structure and processes. Each year in the United States, an average of 8,300 landfill fires occur, most of them in the spring and summer months, as reported by U.S. Fire Administration (2001). Fires in landfills are divided into two categories; surface fires and subsurface fires.

Surface fires involve recently buried or un-compacted refuse, situated on or close to the landfill surface. The presence of methane, a major component of landfill gas, may lead to propagation of the fire throughout the landfill (FEMA 2002). Although this is an exothermic reaction, the ignition temperature of the fuel must be reached through a spark, pilot flame or other heating mechanism (Rynk 2000). Sources of ignition or triggers for surface fire vary between deliberate, accidental, and spontaneous combustion.

Subsurface fires take place deep within the landfill or inside waste piles. Causes of subsurface fire are often related to spontaneous combustion of waste. As sustainable biological activities and exothermic reactions occur, heat starts to build in the waste. If this heat is not dissipated efficiently, temperature will rise until it reaches the auto-ignition temperature of waste material and fire is initiated.

Due to the nature of subsurface fires, determining the extent of subsurface fires is difficult to detect compared to surface fires. Smoke may emanate from cracks far from the fire location. Consequently, extinguishing subsurface fires creates a big challenge. Although dangerous, smoldering material is dug up sometimes to be extinguished by cooling or compacting the excavated material. During this process, flames could spread once smoldering material comes in contact with oxygen. Many other extinguishing methods have been proposed to put this kind of fire out based on actual experience of landfill operators (e.g. closing LFG collectors, injecting water or steam, covering vents with soil, or injecting N<sub>2</sub> or CO<sub>2</sub>).

Detection of subsurface fires is also one of the major problems that landfill operators face. Subsurface fires are often detected by elevated temperature or CO levels in LFG, significant settlements over short period of time, and combustion residue in extraction wells (FEMA 2002). However, Powel et al. (2006) reported detecting carbon monoxide in an aerated landfill with no evidence of temperatures reaching ignition points or fire. They concluded that carbon monoxide was produced as a result of biological degradation of the waste.

Threats of spontaneous fires might extend beyond landfill boundaries and damages associated with deep spontaneous fires can be devastating. Firefighting and sinkholes formed by the spontaneous fires can cause settlement and stability problems for the landfill (El-Fadel et al 1997, Sperling, 2001). A landfill slope failure resulted in the catastrophic deaths of 147 persons in Indonesia. This failure was due to a smoldering landfill fire that damaged the landfill reinforcement (Koelsch et al, 2005).

Subsurface burning of the waste happens in an oxygen deprived environment and at relatively low temperature, leading to emission of air contaminants with higher concentrations than produced by waste incinerator (Sperling and Henderson, 2001). Polychlorinated dibenzodioxins concentrations in air samples from spontaneous landfill fires were found to be much higher than burnt waste samples (Ruokojarvi et al, 1995 a, b). Fires may have long-term negative effects on landfill gas production as a result of inhibition of the methanogenic bacteria by oxygen and combustion products, high temperature, drying of the affected area, and breaking the integrity of cap by settlement, desiccation and firefighting operations (Lewicki, 1999). Another study revealed that landfill leachate is also affected by underground fires and fire fighting activities. COD and heavy metals concentration increased significantly during the fire and the extinguishing period (Oygard et al, 2005)

## **Research Scope and Objectives**

This research investigates subsurface fires that result primarily from spontaneous combustion. The main objectives of this research are to evaluate the occurrence of spontaneous fires in landfills; provide information concerning the initiation, detection and extinguishing of

spontaneous ignition incidents in landfills, and investigate the conditions favoring its occurrence.

Heat generation from biological and chemical degradation activities create the driving force for the spontaneous combustion fires. Therefore, special attention has been paid to the energy balance in municipal solid waste landfills.

## **Dissertation Organization**

This dissertation includes six chapters. Chapter two presents case studies of spontaneous fires and literature review on fire initiation, heat generation in a landfill and factors influencing spontaneous combustion.

Chapter three describes results from a survey distributed to landfill owners and operators regarding spontaneous combustion incidents that happened at their landfills. The survey was designed to collect the landfill owners/operator observations prior to and during the fire. Also, the survey collected detection and extinguishing methods that have been used.

Chapter four describes laboratory experiment conducted on solid waste and solid waste components under different oxidative environments, moisture contents, and leachate contents. A new thermal analytical procedure is proposed based on thermal behavior of solid waste samples during gradual heating. Experimental results are used to evaluate effects of experiment conditions and to compare the thermal behavior of solid waste components alone and collectively.

Chapter five describes the energy balance in landfills. A one-dimensional model has been developed using Microsoft Excel (2003). The model was used to simulate four scenarios representing the most

common conditions in landfills. Chapter six presents the main conclusions and recommendations of this research. Appendices presents the survey used in this study.

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## CHAPTER TWO

### BACKGROUND INFORMATION

The municipal solid waste landfill is often found to be the most economical and environmentally friendly solution for disposal of solid waste. However, landfills are complex systems that promote various interrelated biological and chemical reactions. These reactions are sequential and often lead to processes or incidents that affect the landfill structure or the surrounding environment. Landfill fires are relatively common incidents or problems that landfill operators encounter and have a great impact on the landfill structure and processes. Their causes vary from deliberately set, accidental or spontaneous combustion.

### Case Studies

Each year in the United States, an average of 8,300 landfill fires occur, most of them in the spring and summer months, as reported by U.S. Fire Administration (2001). Also, Ettala et al (1996) reported an average of 380 annual fires in 633 operating sanitary landfills in Finland from 1990-1992. One-quarter of these fires were deep subsurface fires. Amongst fire types, spontaneous subsurface fires are considered the most threatening ones despite the fact that they are relatively infrequent. Their impact can extend beyond landfill boundaries and their damage can be devastating. The following case studies describe spontaneous fires incidents in landfills and compost facilities illustrating importance of spontaneous fires and accompanying events.

#### *Shale Spoils Fire in Dallas, Texas*

Shale deposits excavated from a calcareous bituminous marine shale formation for a sanitary landfill near Dallas, Texas spontaneously combusted. The excavated deposits were piled loosely

in the landfill. The pile grew from September 1999 to August 2000 reaching a maximum height of 15 m. Steam was first observed venting from the pile on August 2000. By September 2000, at least ten steam vents had been identified. Pile surface temperature was recorded to be 130°F (54°C). On October 2000, a few areas near steam vents were excavated. Temperature reached 400°F (204°C) less than 1 m below the pile surface. Further excavation resulted in sudden surges of black smoke followed by white steam and occasionally flames. Maximum temperature exceeded 960°F (516°C) at the core of the hot spot, nearly four meters below the pile surface. The pile continued to smolder until July 2001, when pile material was excavated and spread to cool. Burning of shale spoil stopped in few hours (Hudak, 2002).

Cause of the fire was related to the spontaneous combustion of carbonaceous material in the shale fines. The fines settled through coarser material and accumulated at various locations within the pile. The presence of air, moisture, and fine organic material supported oxidation reactions. These reactions generated heat faster than it could dissipate, leading to combustion (Hudak, 2002).

### ***Bandung Dumpsite Failure in Indonesia***

In February 2005, the Leuwigajah dumpsite in Bandung, Indonesia collapsed. The collapsed waste hit a nearby settlement and killed 147 persons. A stability analysis found that water pressure in the subsoil led to severe damage in landfill structure caused the failure and liberated 2.7 million m<sup>3</sup> of waste in the direction of the settlement. The damage of the reinforcement was caused by a smoldering landfill fire which had burned for months (Koelsch et al, 2005)

### ***Composting Facility Fire in Huron, Ohio***

On February 26, 1996 smoke was noticed coming from a 10 feet high pile of woodchips at the Barnes Nursery Composting Facility in Huron, Ohio. Operators used a dozer and two-wheel loaders in addition to other equipment to break the pile apart, isolate the fire, and spread out the burning material. Also, water was sprayed on the fire. After isolating the fire in one area, smoldering continued and caused a nuisance odor, which raised complaints from downwind neighbors. The same procedure was applied and the fire was extinguished. However, after several days smoke appeared again from the ashes of the original smoldering area. Again, the company moved the material around and added more water. This process continued for over a month when the last section of the smoky chips was smothered on April 4, 1996 using a backhoe to pile on snow, soil and water (Riggle, 1996).

The fire outbreak was initiated by spontaneous combustion. Weather conditions contributed significantly to the outbreak of fire. In January of the same year, the area had a lot of rain followed by a hard freeze that encapsulated the pile and prevented the heat from escaping. At the time of opening the pile, frost was found only about two feet deep and the remaining material was relatively dry (Riggle, 1996).

The Barnes Nursery management consulted a professor at Ohio State University and developed a new strategy. The strategy included windrowing the material in 8 to 12 feet high piles, each 18 feet wide. Another suggested technique to prevent fires in large storage piles is to use a layering technique by building the height of a pile slowly, around one foot per month (Riggle, 1996).

### ***Pilot Composting Facility at Albuquerque, New Mexico***

In May 1995, a 15-feet tall and 50-ft<sup>2</sup> pile of horse bedding and yard trimming from Albuquerque city sources caught fire. The pile consisted of dry and moist material. The pile structure made the problem worse. The pile was built with steep sloping sides. As a result the wind was penetrating the surface rather than flowing over it. Having a good oxygen supply, moisture and organic material favored spontaneous combustion to occur and resulted in a subsurface fire (Riggle, 1996).

Facility operation personnel noticed smoke coming out of the pile then they tried to break open the downwind side to pour water into it. Unfortunately, the problem got worse; as the pile was broken open, the wind picked up the burning material and transferred it to the next pile which spread the fire. Consequently, the fire department was called. Eventually, it was decided to remove all the unburned material and isolate the smoldering fire to extinguish it with water. The fire took about two weeks to extinguish (Riggle, 1996).

### ***Delta Shake and Shingle Landfill Fire, North Delta Canada***

The Delta Shake and Shingle landfill is a privately owned facility located in North Delta, Canada. It was constructed on organic peats, unconsolidated clay and silt. On November 9, 1999, a 250,000-yard<sup>3</sup> cell erupted in flames. Prior to this, steam and smoke had been emerging from the site for several weeks. No one realized that the landfill was on fire until the flame broke through the surface. Immediately, the North Delta fire department was called and the surface fire was extinguished. On November 11, 1999, a 50-yard by 100-yard sinkhole fell about ten feet at

the crest of the cell and flames erupted again, which made the administration realize that the fire was still active deep within the cell.

To extinguish the fire effectively, a consulting company was hired to provide advice. The company considered several solutions; capping the landfill burn area with soil or geomembrane, flooding the burning area with water, injecting CO<sub>2</sub> to displace O<sub>2</sub>, or excavating the burning material and extinguish it with foam. Excavating the burning material was chosen (Sperling, 2001).

To control the blaze, the fire zone was smothered with 6 to 10 feet of refuse, then water was applied to the fire. This procedure was successful in controlling the surface fire. When the surface fire was under control, excavators and trucks were used to move the burning material to cool-down-areas, where burning loads were spread out and foamed. The fire extinguishing process took about two months and cost more than \$2 million-Canadian (Sperling, 2001).

### ***Vancouver Landfill Fire in Vancouver, Canada***

The Vancouver landfill is located in the municipality of Delta, 20km south of Vancouver. The facility is owned and operated by the city of Vancouver and receives about 400,000 metric tonnes of MSW each year. The landfill also receives demolition materials, consisting primarily of wood waste, and uses it in construction of a bedding layer under the MSW.

On October 18, 2000, the facility staff discovered an underground fire. An area of approximately 50 m<sup>2</sup> had settled 60 cm and smoke was venting from it. Steam vents were noticed in the whole

demolition area prior to the subsurface fire discovery. However, concerns of spontaneous fire were not raised. To avoid break out of the fire water was delivered to the burned area using off-road dump trucks and a pumping system conveying water from a dredge pond 2000 m away. To prevent air from entering the fire zone, a silty clay cap was installed along the bank of the demolition area. A monitoring program was installed to follow up firefighting progress and provide recommendations on future actions. The program included installation of subsurface probes to collect gas composition data. Temperature data were not collected because of the relatively shallow fill and the extent of the fire was limited. The monitoring program was completed by November 3, 2000 (Henderson and Sperling, 2001).

## **Combustion**

The combustion process can take many forms, all of which include chemical reaction between combustible species and oxidizers (Drysdale, 1999). Although, combustion is an exothermic reaction, it requires an input of energy to initiate the reaction.

Usually, oxidation reactions are presented in a single step overall reaction. However, the more detailed description is actually a chain of reactions that move through initiation, propagation, and termination steps. A generalized description is presented in equations 1-10:





Equation 2.1 represents the initiation step, where M is a reactant molecule forming a radical R. Reaction 2.2 represents a collection of propagation steps and chain branching to the extent that the overall chain branching ratio can be represented as  $\alpha$ , where  $\alpha$  has any value greater than 1. M' is another reactant molecule. Reaction 2.3 is a particular chain propagating step forming a product P. Since a radical is consumed and formed in reaction 2.3 and since R represents any radical chain carrier, R is written on both sides of this reaction step. Reaction 2.4 is a gas phase termination step forming an intermediate stable molecule I which can react further as M react. Reaction 2.5, which is not considered particularly important, is essentially a chain termination step at high pressures. In step 2.5, R is generally an H radical and RO<sub>2</sub> is HO<sub>2</sub>, a radical much less effective in reacting with stable molecules. Thus reaction 2.5 is considered to be a third-order chain termination step. Reaction 2.6 is a surface termination step which forms minor intermediates I' not crucial to the system (Glassman, 1996).

The chain branching ratio  $\alpha$  plays an important role in determining the reaction continuity to explosion. Thermal explosion takes place when a chemical system undergoes an exothermic reaction during which insufficient heat is removed from the system so that the reaction process becomes self-heating. Since the reaction rate and heat release rate increase exponentially with temperature, the reaction rapidly experience runaway and the system explodes (Glassman, 1996). The critical value for  $\alpha$  is given in equation 2.7:

$$\alpha_{crit} = 1 + \frac{k_4(M) + k_5(O_2)(M) + k_6}{k_2(M)} \quad (2.7)$$

Combustion is divided into two distinct classes based on the mixing of fuel and oxidizer prior to entering the burning zone; premixed combustion and diffusion combustion.

### **Premixed Combustion**

Premixed combustion is the condition at which fuel and oxidizer constituents are completely mixed prior to entering the combustion zone and are in the same physical state (i.e. gas). Conditions at which fuel and oxidizer would undergo explosive reaction are strongly dependent on the pressure and temperature. Given a premixed fuel-oxidizer system at room temperature and ambient pressure, the mixture is essentially unreactive and will not explode. However, if an ignition source is applied locally, raising the temperature substantially, or causes a high concentration of radicals to form, a region of explosive reaction can propagate through the gaseous mixture. Nonetheless, this propagating reaction cannot occur unless the mixture is within certain concentration limits. These limits are called flammability limits (Glassman, 1996).

The flammability limits are the leanest and richest concentrations that will support flame propagation in the mixture. The principal factor that determines the flammability limit is the competition between the rate of heat generation, which is controlled by the reaction rate and the heat of reaction for the limit mixture, and the external heat loss by the flame (Glassman, 1996).

An important parameter that affects flammability and ignition phenomena is wall quenching or quenching diameter. It is the diameter of the tube that prevents flame from propagating inside the

tube. The flame is quenched in a tube when diffusion of species and heat is affected. The tube walls extract heat more efficiently as the tube diameter get smaller since it will mean a greater surface area to volume ratio and hence a greater volumetric heat loss. Furthermore, reducing the tube diameter increases the surface termination of radicals and the fewer number of collisions of the active radical species (Glassman, 1996).

### ***Diffusion Combustion***

Diffusion combustion occurs when the fuel and oxidizer constituents are separated before burning either because they are in different physical states or both are in the gaseous phase but are not mixed prior to burning (Drysdale, 1999). In this type of combustion, chemical reactions are fast relative to mixing rates so that combustion rates are controlled by the rate of mixing. Since mixing is controlled by diffusion, the reaction rate depends primarily on the diffusion rates of fuel and oxidizer into the mixing zone. Examples of diffusion flames are the combustion of liquid fuels (e.g. diesel) and solid fuels (e.g. coal) (Drysdale, 1999).

The diffusion of solid and liquid fuel molecules is more complicated than gaseous fuels. Liquid and solid fuel molecules need to evaporate or gasify from their original state and mix with the oxidizer. In contrast, some solid materials have negligible vapor pressure so significant amounts of these materials simply cannot enter the gas phase to react with oxidizer. In this case, combustion occurs by reaction of exposed fuel molecules at the solid surface with gas phase species that are transported in from the environment (Drysdale, 1999). Intuitively, flammability limits do not hold in diffusion combustion as in the premixed combustion due to the fact that mixing of fuel and oxidizer cannot be controlled.

## **Ignition and Propagation**

Ignition may be defined as a rapid transition process by which self-sustained combustion is initiated (Kuo, 1986; Drysdale, 1999). The presence of heat, oxygen and fuel (i.e. solid waste) in the landfill creates the necessary elements for a fire. However, the progressive self-heating reactions for a fuel/oxidizer (solid waste/oxygen) mixture will take a period of time before fire initiates, referred to as the induction time (Gray, 2002). This time interval can be related to the temperature of the mixture. If the temperature is maintained below the auto-ignition temperature (AIT), ignition does not occur even after an extended period of time (Glassman, 1996). Basically, the AIT is the temperature at which elements of the fuel-oxidizer system enter into the ignition regime; for example the ignition temperature for methane, a by-product of waste degradation, is 500°C. This temperature can be reached by a direct pilot source (i.e. flame) or high ambient temperature (i.e. spontaneous combustion). In fact, spontaneous ignition requires a higher heat flux than pilot ignition because a higher surface temperature is required. For example, using a convective heat source, wood burns spontaneously at 490°C while with pilot ignition it burns at 450°C, (Kanury, 1972 and Drysdale, 1999). Once fire is initiated, combustion is maintained by self-sustained heating.

Once ignition occurs, it is assumed that smoldering (fire propagation) is self-sustaining as long as heat generation is sufficient to dry the waste and drive combustion. Propagation of smolder is controlled to a large degree by the rate of oxygen transport to the reaction zone, because the heat evolved during smolder initiation raises the local temperature and thus the local reaction rate until all of the neighboring oxygen is consumed. Subsequently, the reaction continues to

consume oxygen as fast as it reaches the reaction zone (Ohlemiller, 2002). Accordingly, two types of smoldering spread can be classified based on the direction of oxygen transport. In the one-dimensional spread, when the oxygen diffuses in the direction towards the smolder reaction front, the smolder spread is termed reverse spread. On the other hand, if the transport of oxygen is in the same direction as the smolder spread, a forward spread results (Puri, 1993). In landfill smoldering fires, reverse combustion is assumed because oxygen is typically supplied from the surface and ignition occurs deep within the landfill and propagates outward (Fatehi and Kaviany, 1997). Given the large solid fuel concentration, limited porosity, and low oxygen levels in a typical landfill, flaming is unlikely unless the smoldering waste is exposed to the atmosphere, at which time gas-phase oxidation occurs and high temperature combustion is achieved (Fatehi and Kaviany, 1997).

Generally, fire propagation following ignition in heterogeneous combustible media is the result of heat transfer between a gaseous phase and solid particles (Larini et al, 1998). Fire propagation in porous media is usually referred to as smoldering which is a slow, low temperature and flameless form of combustion (Ohlemiller, 2002). Smoldering can be self-sustained if the condensed-phase fuel is porous and forms a char (Puri, 1993). As the temperature exceeds 100° C, waste components such as wood slowly char. The charred wood may generate heat through adsorption of oxygen and other gases. At these temperatures, chemical reactions with oxygen progress at increasing rates as the temperature rises to the point of ignition. Smolder propagates by means of heat evolution either from the exothermic oxidative degradation of the fuel, from the subsequent oxidation of char, or both (Puri, 1993).

Spontaneous ignition occurs when material is heated beyond the AIT. Heating happens inside the landfill due to different natural exothermic reactions in a process referred to as self-heating. Spontaneous ignition in landfills develops primarily when self heating of the solid waste occurs at a rate higher than the heat dissipation rate. Heat generated within a waste pile is usually dissipated through its surface. As the size of the pile increases, the surface to volume ratio decrease. Therefore cooling significantly reduces as the size of the landfill is increased.

Self-heating takes place as a result of the degradation and decomposition of solid waste. Solid waste is primarily composed of degradable organic material that decomposes exothermically. Degradation processes can be both chemically and biochemically mediated, however biochemical reactions predominate at temperatures below 65°C (Storm, 1985). Unless hot loads were dumped at the landfill, biochemical reactions are solely responsible for increasing the solid waste temperature from ambient temperature to ~65 °C. It is well known that microorganisms are capable of reducing the activation energy of chemical reactions and encouraging exothermic reactions to occur. Chemical reactions do not have significant contribution to heat generation below ~65 °C because of the low oxidation rate of solid waste. As the temperature of the solid waste increases chemical reactions become more influential and become the primary source of heat generation at temperatures higher than 65°C.

### **Biological Self Heating**

The biological digestion of the organic matter in a landfill normally occurs in two phases, a very brief initial aerobic decomposition phase followed by anaerobic decomposition after oxygen is depleted. Although both of these biological processes basically break large complex organic

compounds into small compounds, reaction products and heat release are different. Aerobic processes decompose organic solid waste into carbon dioxide and water and release a significant amount of heat which can cause an increase in landfill temperature (Robinson, 1986 and El-Fadel, 1999). Anaerobic processes decompose solid waste into methane and carbon dioxide and release less heat. As an example, aerobic transformation of glucose as representative of the organic matter in the waste can be expressed by Equation 2.8 (Meraz and Dominguez, 1998):



While transformation of glucose under anaerobic condition can be expressed by Equation 2.9:



Comparing the enthalpies of the two reactions, it can be noted that heat generated in anaerobic decomposition is about 5% of the heat produced from aerobic reactions and the bulk of the remaining energy is stored in methane (Meraz and Dominguez, 1998 and El-Fadel, 1999). The amount of heat generated in solid waste relative to methane produced varies to some degree depending on the material decomposed (Augenstein, 1999). The decrease in heat generation during the change from aerobic to anaerobic decomposition may temporarily stabilize landfill internal temperature, however insulating properties of the refuse minimize heat flux from the landfill to the surroundings and temperature will ultimately continue to rise (Rees, 1980, El-Fadel, 1999).

## **Chemical Self-Heating**

In a landfill environment, self-heating due to chemical reactions is believed to involve a number of exothermic reactions. Among these reactions, chemical oxidation and pyrolysis are considered as the most significant. Chemical oxidation and pyrolysis dominate the thermal degradation of solid waste at different ranges of temperature. At relatively low temperature (70-190 °C), chemical oxidation governs the degradation process, influenced primarily by the presence of oxygen. At higher temperatures, pyrolysis, decomposition due to heat only, becomes more influential in decomposition of solid resulting in high ambient temperature and energy release (Shafizadeh and Bradbury, 1979).

### ***Chemical Oxidation***

Although chemical oxidation is similar to aerobic biological degradation in terms of the final products and total released heat, rates of heat generation and oxygen consumption are higher during chemical oxidation. This difference can be explained by the relationship between reaction rates and temperature; higher temperatures reached during chemical oxidation allow more reactant materials to rapidly obtain the necessary activation energy. Moreover, microorganisms consume energy and carbon during biochemical degradation for growth and maintenance. Springer et al (1971) studied spontaneous heating in piled wood chips. In this study, they measured the oxygen consumption and calculated the released heat for aspen and Douglas-fir wood during biological degradation and chemical oxidation. They found that oxygen consumption during biological activities was about 39% and 50% of the oxygen consumption during chemical oxidation for aspen and Douglas-fir wood, respectively.

Other heat generating reactions can develop in the landfill when by-products of chemical oxidation and biological decomposition are produced in the same environment. In the presence of rust, created from landfilled steel oxidation, and hydrogen sulfide generated biologically, iron sulfide can be produced as shown in Equation 2.10:

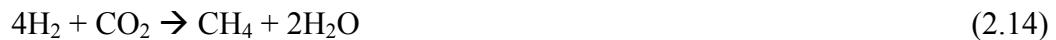


Oxidation of the FeS formed is highly pyrophoric (i.e. highly reactive and can ignite upon contact with oxygen, Walker et al, 1996), as shown in Equation 2.11.



The ratio of hydrogen sulfide to oxygen can be critical in favoring the formation of pyrophoric sulfide (Hughes et al, 1976). Hughes et al found that when oxygen was less than 10% by volume, sulfide was oxidized in a controlled, slow manner, while oxygen above 10% by volume favored pyrophoric oxidation. Furthermore, dry FeS has been shown to be pyrophoric in air with a relative humidity above about 50% while oxidation is slow and controlled below 50% (Walker et al, 1988). This reaction has not been confirmed to be a source of heat generation in landfills, but given the large amount of iron and sulfur typically found in landfills, it likely to contribute to temperature rise if oxygen is present.

Another type of chemical heat-generating reactions under anaerobic conditions has not received much attention, although it could add substantial quantities of heat (Augenstein, 1999). Reactions of scrap iron and carbonate are shown in Equations 2.12-2.14, (Augenstein, 1999):



The net, overall reaction and enthalpy change is



The presence of metals or metal salts in solid waste may play a significant role in self-heating within a landfill by serving as a catalyst for chemical reactions. According to Buggeln and Rynk (2002), operators of composting and mulching sites reported the existence of “tramp metal” in charred cavities after a spontaneous combustion event; however, the effect of the tramp metal has not been explained. Metal salts have been proven to have an influence on temperature during heating experiments. Sujanti and Zhang (1999) showed that adding inorganic compounds to samples of coal bed created the highest reactivity and lowest critical temperatures at which reaction occurred. Also, Walker and Harrison (1977) studied the addition of ferric oxide to sawdust and reported an increase in pyrolysis and oxidation rates.

Another possible source of heat generation in landfills is the reaction of aluminum dross with water. Reactions associated with disposal of aluminum dross were found to be a potential source of heat generation at the Countywide Landfill in Ohio, US. The landfill accepted about 600,000 tons of aluminum process waste between 1993 and 2001. Between 2001 and 2006 operators reported elevated temperatures at landfill gas wells and received numerous complaints of odor. Later rapid settlement and changes in landfill gas composition were observed (EPA, 2008). Aluminum dross can be described as a scum formed during production of aluminum. It is occasionally placed in landfills where upon contact with water highly exothermic reactions occur. Aluminium carbide, nitride, and phosphide represent some of the major dross salts that react with water, even with moisture in air, according to the following reactions, (Shinzato and Hypolito, 2005):



However little information is available about their presence in landfills and their reactivity.

### ***Pyrolysis***

Pyrolysis can be defined as chemical degradation of large organic compounds under applied heat. Solid waste is believed to go through pyrolysis as temperature rises. Kubler (1982a) provided an extensive review of wood pyrolysis and showed that pyrolysis can be exothermic or endothermic, depending on the temperature and duration of heating. Kubler (1982a) identified

two categories of pyrolysis, slow pyrolysis and fast pyrolysis. Slow pyrolysis is an exothermic process and is related to a multi-step decomposition of complex compounds at low temperatures, coupled with hydrolysis and oxidation, resulting in the production of water, CO<sub>2</sub>, and heat. Produced CO<sub>2</sub> dissolves in water forming a weak acid which accelerates abiotic decomposition processes that form small organic compounds. Fast pyrolysis, however, is characterized by vigorous reactions at high temperatures (above 190°C). These reactions are endothermic; they consume energy and produce high energy content products such as volatile gases, liquid tars and solid char (Buggeln and Rynk, 2002). Pyrolysis of cellulose (a major compound in paper, cardboard, yard waste and textile) is generally endothermic except at low heating rates and in confined environments that limit mass transfer and promote char formation. Energy release is estimated at 2kJ/g of char formed (Kanury, 1972; Milosavljevic et al, 1996).

Shafizadeh and Bradbury (1979) studied thermal degradation of cellulose in air and N<sub>2</sub> at low and high temperatures. They monitored the degree of polymerization of purified cellulose, residual cellulose weight, and the yield of CO and CO<sub>2</sub>. They found that at temperature higher than 300°C pyrolysis surpasses the effects of oxygen; while at temperatures lower than 300°C, oxidation plays the major role and proceeds faster than pyrolysis.

## **Heat Loss**

Heat can be lost from the landfill by several mechanisms including water evaporation, convection, and conduction. Heat loss by evaporation occurs as water surrounding the solid waste absorbs the heat and evaporates. Latent heat of evaporation and high specific heat for water are major heat sinks inside the landfill. However, as gas currents carry the water vapor

from a hot spot and move to areas with lower temperature, water vapor condense releasing high levels of heat energy.

Convective heat loss, transfer of heat between solids and fluids, depends on temperature differences between the porous solid material and the moving gas or liquid, solid waste porosity, gas or liquid velocity, and degree of saturation. Heat loss by convection can be more influential in a landfill because of the movement of gas and liquid. Generally, heat loss by convection to gases is low; however, recirculation of leachate or addition of other liquids can be influential in dissipating the heat by convection as liquids have higher heat transfer capacity than gases.

Conductive heat loss, transfer of heat through solids, depends primarily on the temperature differential, thermal conductivity and solid waste mass. Except for metals, solid waste components in general have low thermal conductivity, between 0.1 - 0.8 W/kg.K (Lanini et al 2001 and Gholamifard et al 2008). Therefore, heat loss by conduction can be very low.

## Air Intrusion

Air flow in the landfill structure has a critical effect on biological and chemical processes. Generally, oxygen entrapped in recently packed waste in the landfill body is consumed rapidly as aerobic decomposition takes place, reaching a point at which oxygen levels cannot sustain aerobic digestion, and the degradation process evolves to anaerobic digestion. However, cracks, poor cover conditions, boreholes, damaged gas wells, inappropriately placed gas wells, strong winds, and overdrawing of landfill gas (LFG) can deliver oxygen to the digestion zone (Stearns, 1984; Ettala et al, 1996; Lewicki, 1999). Consequently, aerobic degradation can begin again,

more heat may be produced, and temperature of the solid waste will increase. The chimney effect, which draws humid and warm air into the landfill as high temperature gas moves and expands upward, can cause air to flow through the landfill body, delivering oxygen to the heat generating processes. Moreover, change in atmospheric pressure can move landfill gas out or move air into the landfill body (Young, 1992; Nastev et al, 2001; Ishigaki et al, 2005).

Use of soil or clay as a daily cover, compacting the solid waste, and overburden stress decreases the air permeability deep inside the landfill, which may insulate the waste resulting in heat trapping or conversely, can block the needed oxygen from reaching the reaction zone (Kubler, 1982b; Jain et al, 2005). In a study of wood chips piles, Kubler (1982b) evaluated the heat generation and heat lost by convection currents. Kubler (1982b) concluded that air convection can be a very effective method to avoid self-heating in wood chips assuming adequate air flow rate through the material is provided (i.e. no compaction, no convection barriers added and fine particulate elements).

## **Moisture**

Researchers have been investigating injection of air and moisture in bioreactor landfills because of the ability of aerobic landfills to degrade the solid waste at higher rates than conventional anaerobic landfills (Stessel and Murphy, 1992; Read et al, 2001 a,b; Reinhart et al, 2002). However, aerobic bioreactors run the risk of self heating and spontaneous combustion unless adequate methods have been provided to dissipate heat, such as moisture addition.

Solid waste tends to absorb significant amounts of moisture, as received solid waste has moisture content of approximately 20-30% by weight (Vesilind et al., 2002), but field capacity can be as high as 40% by weight (Reinhart et al, 2002). Moisture is a key factor in solid waste degradation, whether biologically or chemically mediated. Microorganisms require water for their metabolic activities; therefore, water can be a limiting element in biological self-heating (Walker, 1967). Moisture may also be significant in controlling spontaneous combustion. Moisture movement can result in transfer of heat by removing the latent heat of evaporation from hot surfaces and perhaps conveying it to cooler locations where water vapor condenses. Moreover, high moisture content may block air passage to the reaction zone (Jain et al 2005).

The introduction of leachate recirculation at a temperature lower than the landfilled waste temperature can result in short-term solid waste cooling. After the leachate is added, temperature of the solid waste will rise due to the enhanced biological activity. Kumar (2007) presented data where a short-term temperature drop occurred after leachate injection followed by temperature increase at a rate of 5°C/year.

Moisture was found to be an accelerator for the chemical oxidation of different materials including coal, yard waste and wood chips (Brownring and Crone, 1950, Shea and Hsu, 1972, Kubler, 1987, Buggeln and Rynk, 2002, Kucuk et al, 2003, Kadioglu and Varamaz, 2003). Thompson (1928) studied atmospheric oxidation of linseed oil on cotton waste at 100°C and observed that the presence of limited amounts of moisture increased the rate of heat production. However, moisture influence had an optimum range through which it functioned as an accelerator; outside this range it may not have any effect or may limit the self-heating process

(Rynk, 2000, Buggeln and Rynk, 2002, Kucuk et al, 2003). Rynk (2000) reported that the critical moisture range for spontaneous combustion in compost facilities is 20 to 45 % by weight; moisture content below 25% is not sufficient to support biological activities, and above 45%, available moisture will consume heat as it evaporates which will limit temperatures rise. Kawatra and Hess (1999) studied spontaneous heating of machine swarf (a waste stream from machining of metal components, consisting of finely divided iron powder) at different moisture contents (10, 15, 20, 25, and 30% by weight) and reported that the maximum heat release was attained at 15% and that spontaneous heating for swarf was more likely when moisture content was 10 to 25%, by weight.

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## CHAPTER THREE

### SPONTANEOUS COMBUSTION FIRES IN MSW LANDFILLS

#### **Background Information**

Spontaneous combustion landfill fire incidents are significant problems for landfill operators and owners. The sequence of events and the incidents themselves can result in catastrophic losses. Generally, landfill fires present health hazards to the community. Smoke and other byproducts such as particulate matter can cause pulmonary or respiratory health risks. Smoldering fires have been found to release substantially higher levels of toxic compounds than flaming fire (Ohlemiller, 2002). Burning of the waste generally happens in an oxygen-deprived environment and at relatively low temperature, leading to the emission of products of incomplete combustion at higher concentrations than produced by waste incinerators (Sperling and Henderson, 2001). Polychlorinated dibenzodioxins concentrations in air samples from spontaneous combustion landfill fires were found to be much higher than burned waste samples (Ruokojarvi et al 1995 a, b; Ettala et al, 1996). Furthermore, subsurface fires result in high levels of CO ( $> 50,000$  ppm) far exceeding the OSHA permitted level of 50 ppm. Other toxins such as dioxins may be formed and released into the air during the combustion process. Exposure to dioxins is linked to cancer, liver damage, and reproductive and developmental disorders (FEMA, 2002).

Detection of spontaneous combustion fires is a challenge to landfill operators. Researchers have identified different approaches to detect underground fires and determine their extent. Stearns and Petyan (1984) and Lewicki (1999) investigated underground fires through monitoring and operation in landfills and proposed a procedure to spot fires as early as possible. In both studies, detection was based on the ground settlement, gas composition and temperature, measuring

subsurface temperatures, carbon monoxide concentration and thermal imaging. To prevent fires, those studies proposed implementing systematic monitoring of landfill structure and LFG composition, thermal imaging of the landfill, and proper handling of waste.

Riquier et al (2003) used three methods to investigate the presence of underground fire in two landfills; measurement with an infra-red camera, geophysical (electric and electromagnetic) methods, and gas measurement in subsurface boreholes. The authors reported an increase in concentrations of carbon monoxide, nitrate, ammonia, sulfur oxides, cyanides, and several types of volatile organic compounds near fires or test boreholes. The study recommended using a combination of investigation methods; infra-red cartography to locate disruptions in the topography coupled with geophysical measurement to investigate temperature at depth, followed by monitoring changes in gas composition. Moreover, Riquier et al (2003) reported similarities with underground fires in both landfills including perturbations in biogas composition and systematic presence of oxygen near the fire outbreak. Riviere et al (2003) used a portable method to localize combustion in landfills; using 2D-electrical and electromagnetic (Slingram) surveys. The electrical method was used to show the cell structure and any deep changes. The electromagnetic method was used to localize anomalies in the top cover conductivity. The authors recommended using the electromagnetic method to detect any anomaly quickly, since it is easy to implement, and then use the electrical method to accurately locate the phenomena and its extent.

Carbon monoxide has been used frequently as an indicator of fire; however, recent studies revealed that carbon monoxide is produced naturally during biological activities (Engel et al,

1972, Conrad and Seller, 1985, Hellebrand, 1998, Hellebrand and Kalk, 2001, Goedde et al, 2000, Svedberg et al, 2004, Powell et al, 2006). Therefore, it is important to study the landfill gas composition before and after the fire has occurred. Powel et al. (2006) detected carbon monoxide in an aerated landfill with no evidence of temperatures reaching ignition points or fire. They concluded that carbon monoxide was produced as a result of biological degradation of the waste under limited oxygen conditions.

Extinguishing subsurface fires is more difficult than surface fires. During the extinguishing process, flames could develop once smoldering material comes in contact with air. Nevertheless, smoldering material is occasionally excavated to be extinguished by cooling or compacting the burning material which may jeopardize firefighter safety. Inability to determine the location and the extent of fire makes extinguishing subsurface fires more complicated. Extinguishing methods are primarily based on preventing oxygen from accessing the combustion zone by covering vents with soil or cooling the waste material below ignition temperatures (Stearns and Petoyan, 1984). However, once material reaches exothermic pyrolysis, the presence of oxygen becomes unnecessary to sustain the thermal degradation and self-heating. Also, spraying water on the surface or injecting water to cool the combustion zone may not be effective if water is blocked from infiltrating to the combustion zone by compacted waste or diverted through channels inside the landfill cell structure that bypass the fire. Moreover, being unable to determine the fire location and using inefficient extinguishing method may extend the extinguishing process, increase the fire damage, and increase extinguishing cost.

This study explores the causes of spontaneous landfill fires and remediation procedures. The purpose of this work is to review detection and extinguishing methods used by landfill operators, collect information on conditions during and prior to the fire, and draws inferences on landfill spontaneous fires and landfill operational conditions from actual observation.

## **Methodology**

### ***Questionnaire***

A web-based questionnaire was created and distributed to US landfill operators through The Solid Waste of North America (SWANA) and National Solid Waste Management Association (NSWMA). Also, directors of US environmental protection state solid waste divisions in all 50 states were contacted by email and asked to forward the questionnaire to landfill managers or operators in their state. In addition, 100 copies were distributed to landfills in states without a database of email addresses.

The survey was divided into two parts; description of the landfill and its operational conditions and description of subsurface fire incidents. The landfill description part focused on cell structure and operation, solid waste characteristics and treatment, and historical records of previous fires. The subsurface fire incidents description part focused on events associated with fire incidents, detection, and extinguishing methods used. Responders were given multiple choices to choose from and a space to report other events, incidents, or observations they have witnessed. A copy of the survey is provided in Appendix A.

## **Results and Discussion**

### ***Responses***

Thirty-seven responses were received regarding landfill fire. Out of these 37 responders, only 22 reported incidents of subsurface fires. The remaining responses described surface fires.

Subsurface fire responses came from landfills including both cells constructed aboveground and underground. Landfill fires occurred in lined and unlined cells. Also, responses reported fires in conventional landfills as well as landfill practicing leachate recirculation. However, solid waste moisture content was not provided. Responders reported experiencing spontaneous subsurface fires in all types of waste; commercial, municipal, industrial, and construction and demolition. Separate fires inside waste pile were also reported. Fires in piles of wood chips, yard waste, mulch, tires, and manure piles were described. Cell ages at fire varied between 11 months and 19 years.

Generally, results showed no relationship between spontaneous fire and landfill type, solid waste types, or leachate recirculation. Also, results indicated no relationship between spontaneous fires and landfill age.

### ***Events Prior to Fire***

In this part of the survey, events that preceded the spontaneous combustion fire were described. Figure 3.1 shows the percentage of prior-fire events according to the responses received. Events prior to fire included rain, strong winds, dumping of hot loads, or aggressive landfill gas

extraction. Others include dumping special industrial waste or reactive waste. Results suggest changes in moisture content, intrusion of air and high temperature loads are the primary motivators of spontaneous subsurface fires.

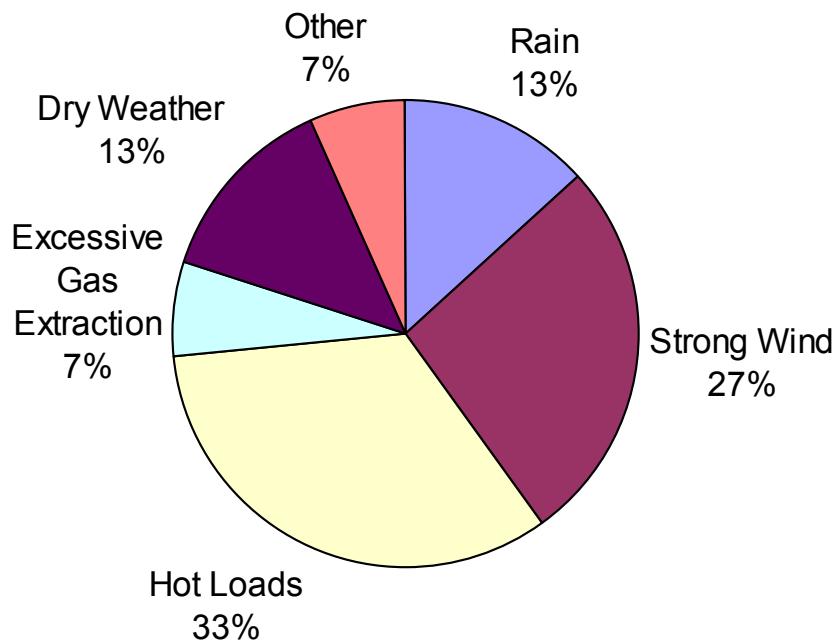


Figure 3.1: Events Prior to Fire

### ***Detection Methods***

Survey results showed that fire was detected 59% of the time by observing smoke or steam emitted from the surface. About 23% of the responses indicated detection of fire by changes in the landfill surface, i.e. sudden depression (13%) and cap cracks (10%). Five percent of the responses reported detection by high concentration of carbon monoxide and 3% for interruption in LFG flow. The remaining 10% reported other methods including high temperature in LFG,

and flames and smoke from leachate collection system at the time of shutdown for maintenance. None of the responders reported using graphic scanning to detect subsurface fire. Figure 3.2 shows responses to the survey.

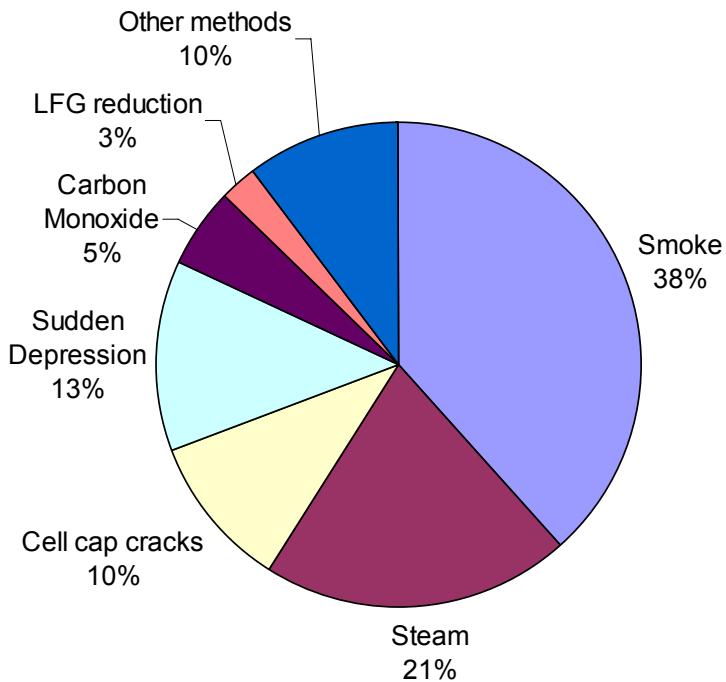


Figure 3.2: Fire Detection Methods

### ***Extinguishing Methods***

Generally, extinguishing methods were based either on preventing air from accessing the smoldering area or cooling the burning material. The study showed that the primary extinguishing methods are excavation the burning waste (40%) and covering it with soil (29%). See Figure 3.3. Extinguishing by water has been used regularly (17%), but not as the sole method; it is always combined with soil cover, excavation of burning material, or both. Reason for not being able to extinguish the fire by water only might be the dual effects of water of

cooling the burning solid waste while stimulating degradation and contribute to temperature elevation. Also, water might follow preferential paths through the solid waste and flow away from the smoldering area. Inert gas injection was not commonly used, only 3% of landfills reported using inert gas injection. Almost 11% reported using other methods including covering waste with foam or a geomembrane and shutting down the LFG extraction system.

Survey results illustrated a wide variety of extinguishing time periods varying between a few hours in some cases to one year. See Figure 3.4. Approximately 38% reported extinguishing the fire within the first 24 hours from discovery of the fire. Around 31% reported extinguishing the fire within a week, 8% reported that fire control took one week to a month, while 23% reported a month to one year was needed to extinguish the fire. Survey results indicate that there is no typical period for extinguishing the fire and fire fighting can take a very long time.

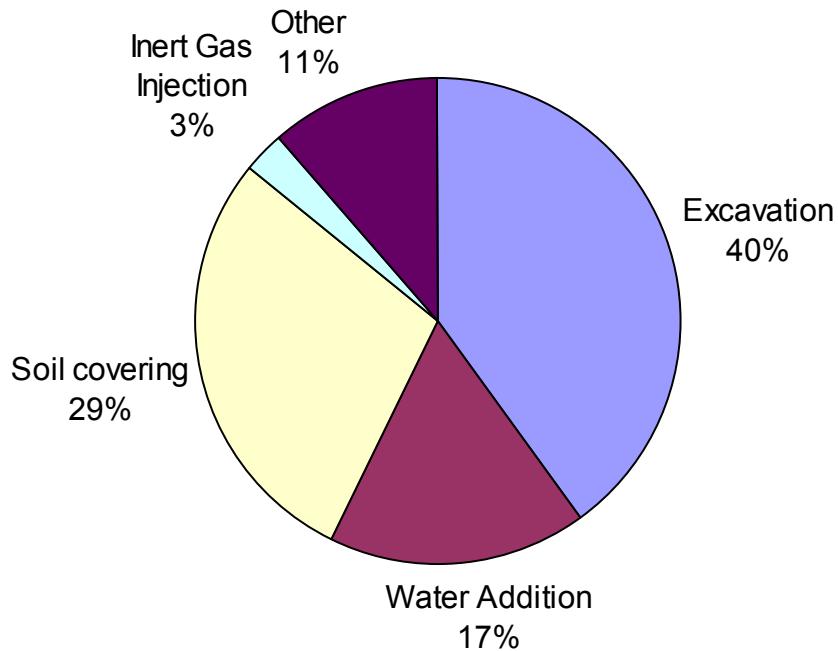


Figure 3.3: Fire Extinguishing Methods

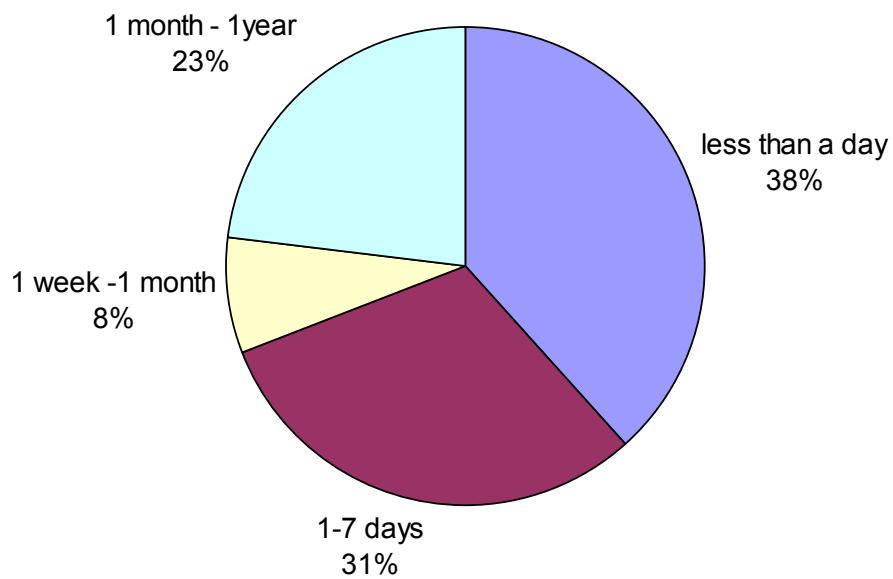


Figure 3.4: Fire Extinguishing Period

### ***Events During the Fire***

A common series of events usually occurs during the fire that can create safety hazards or physically impact the landfill according to survey responses. Figure 3.5 shows events taking place during the fire and their percentages. These events include eruption of flames (34%), obnoxious smell (28%), formation of haze (10%), and collapse of the landfill surface (21%). The survey demonstrates that flames, odor, and surface collapse are the dominant problems in fire incidents. Other events (7%) included emission of incomplete combustion products and leachate seepage as a result of fire extinguishing activities.

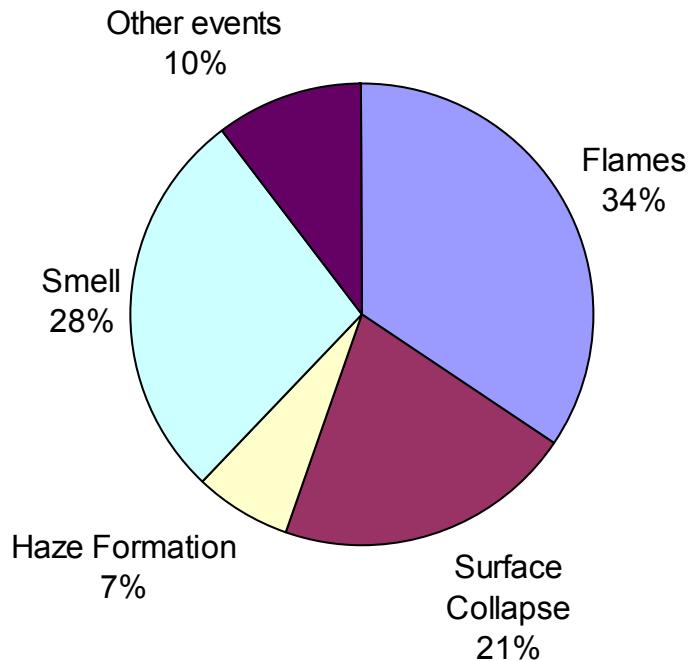


Figure 3.5: Events During the Fire

## **Conclusions**

Subsurface fires are occasional incidents but can have severe repercussions for landfill operators and the surrounding community. Spontaneous combustion occurs when materials are heated beyond the auto-ignition temperature. Temperature rise occurs inside the landfill due to exothermic reactions which cause self-heating of the solid waste. Oxygen introduction leading to biological waste degradation and chemical oxidation is believed to be the main causes of rising solid waste temperatures to the point of ignition. Moisture content plays an influential role in promoting as well as controlling spontaneous subsurface fires.

Survey results confirmed literature observations and raised new questions necessitating further study of subsurface fires incidents. Subsurface spontaneous fires are not restricted to any landfill geometry or type of waste (municipal, industrial, commercial, and construction and demolition). Also, survey results showed occurrence of fires in landfills that are operated with and without leachate recirculation.

Survey responses suggested intrusion of air, change of moisture content, and increase in temperature due to hot loads as possible causes for subsurface fires. A quantitative study of these factors is expected to answer more questions on fire conditions. Also, survey results indicated that cooling the burning solid waste by extraction and compaction are the most effective methods for extinguishing subsurface fires.

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## CHAPTER FOUR

### FACTORS INFLUENCING THE SPONTANEOUS COMBUSTION IN LANDFILLS

#### **Background**

Landfills are complex systems that promote various interrelated biological and chemical reactions that result in waste degradation. Degradation processes can be both chemically and biochemically mediated, however biochemical reactions predominate at temperatures below 65°C (Storm, 1985). Generally, chemical oxidation of solid waste occurs at temperatures as low as room temperature; however, the oxidation rate is very low. An increase in ambient temperature causes an increase in oxidation rate and concomitantly heat generation rate, according to Arrhenius relationship. The presence of heat, oxygen and fuel (i.e. solid waste) in the landfill creates the necessary elements of a fire. If this heat is not dissipated efficiently, temperature will rise until it reaches the auto-ignition temperature (AIT) of the solid waste causing fire to initiate.

Landfill fires are common incidents that pose significant challenge to landfill operators. These fires range from small and easily extinguished surface fires to large and obscured underground fires. Amongst fire types, spontaneous subsurface fires are considered the most threatening ones despite the fact that they are relatively infrequent. Their impact can extend beyond landfill boundaries and their damage can be devastating. Rapid oxidation of the solid waste within the landfill can weaken the landfill structure and disturb its stability. Moreover, subsurface fires can impact the integrity of the landfill cap, leachate quality and landfill gas generation due to high temperature, settlement, desiccation and firefighting operations (Lewicki, 1999; Oygard et al,

2005). In addition, subsurface fires present a significant threat to the environment by emitting incomplete combustion products and air pollutants to the atmosphere such as polychlorinated dibenzodioxins and dibenzofuran (Nammari et al, 2004).

Spontaneous combustion fires have been reported in different types of stored material such as coal, hay, mulch, tires, manure, compost as well as landfilled solid waste (Rothbaum, 1963; Yoshida et al, 1999; Hill and Quintiere, 2000; Kadioglu and Varamaz, 2002; Schmidt et al, 2003; Kucuk et al, 2003; Shah et al, 2004; Lu et al, 2004; and Vantelon et al, 2005). Few studies were conducted on spontaneous combustion in landfills and little data was presented on this topic. On the other hand, numerous studies were done on spontaneous combustion of solid fuel, mainly coal (Sujanti et al, 1999; Hill and Quintiere, 2000, Kadioglu and Varamaz, 2002, Schmidt et al, 2003, Kucuk et al, 2003, Lu et al, 2004 and Vantelon et al, 2005). The fact that solid waste contains high concentrations of combustible materials suggests that it will ignite in a similar manner to solid fuel.

Ignition may be defined as a rapid transition process by which an exothermic reaction and self-sustained combustion is initiated (Kuo, 1986; Drysdale, 1999). Combustion of solids can develop in two ways: flammable combustion caused by burning of volatilized compounds and smoldering, flameless combustion (Kuo, 1986). Many theories were proposed to explain the mechanisms of solids ignition. Described by Price et al (1966) then re-presented by Kuo (1986), solids ignition theories are grouped into three categories: gas-phase ignition, heterogeneous ignition, and solid-phase ignition. The gas-phase ignition occurs in a vaporized solid material and ambient air mixture. Heterogeneous ignition occurs at the interface between ambient air and

the solid phase. Solid-phase ignition depends on either the amount of heat released by subsurface chemical reactions or external heating. The steps of solids ignition were described in literature as follows: an increase in solids temperature, decomposition of the solid phase, escape of volatiles from the solid surface, diffusion of pyrolyzed species from the solid surface into the ambient air, diffusion of oxygen to the reaction sites on the solid surface followed by gaseous reactions in ambient air and heterogeneous reactions at the solid surface.

Generally, landfills contain a mixture of solid wastes and each component has different thermal characteristics and behavior, which controls spontaneous combustion. Thus, it is important to identify the role of each waste component in landfill spontaneous combustion and which component is more susceptible to ignite spontaneously.

In addition, the literature indicates that spontaneous combustion is influenced by several factors (Stearns and Petoyan, 1984; Kubler, 1987; Ettala et al, 1996; Kawatra and Hess, 1999; Rynk, 2000; Mehaffey et al, 2000; Buggeln and Rynk, 2002; Hogland and Marques, 2003; Schmidt et al, 2003; and Wallner et al, 2003) including moisture content, oxygen concentration, temperature, and presence of catalysts. In landfills, these factors vary with time and sometimes are difficult to control because of the structure of the landfill or heterogeneity of solid waste.

The severity of fire impacts creates a need to understand spontaneous combustion and to control it. Accordingly, characterizing spontaneous fires and factors influencing fire initiation and propagation in landfills is needed. Solid waste consists of a variety of different components; therefore, it is important to study the thermal behavior of each solid component. This study

investigates the spontaneous combustion of major solid waste components and proposes a methodology to understand the conditions and factors that influence spontaneous combustion initiation. The purpose of these experiments is to study the thermal behavior of solid waste under different environmental conditions and identify those that are believed to be critical to spontaneous ignition of solid waste.

## **Materials and Methods**

### ***Equipment***

Tests were conducted using a programmable muffle furnace (Fisher Scientific – Isotemp Programmable Muffle Furnace, Model 126). The furnace included a gas injection port to control the atmosphere inside the furnace and was equipped with an exhaust tube connected directly to a fume hood. The samples were placed in a cylindrical mesh steel basket (8.6 cm ID x 10 cm height). Temperature measurements were made using three type-K thermocouples fixed at the sample center and surface and in the furnace chamber. Data from thermocouples were collected every minute using a data logger (QuadTemp -Madge Tech) that was connected to a personal computer. Oxygen concentration was monitored continuously during the tests using an Oxygen/Carbon Dioxide Analyzer (model 3750 - Illinois Instruments, Inc). The system diagram is shown in Figure 4.1.

### ***Material***

Combustible solid waste test materials were selected that represent typical components of municipal solid waste (MSW). Also, a mixture of solid waste was synthesized according to the typical composition of MSW (Vesilind et al, 2002). Table 4.1 identifies the waste components

that were tested, preparation method, typical energy content and weight per test container. Samples were placed in a steel mesh basket and compacted by hand. Then, to investigate the behavior under different oxidative environments, the furnace chamber environment was injected with saturated air or a gas mixture to represent 21%, 10%, or 0% by volume oxygen (the balance was dry nitrogen). The sample moisture content was adjusted by drying the samples at 104°C for 24 hrs then adding de-ionized (DI) water to dry samples using a fine sprayer until the required percentage of moisture (10%, 20%, 30%, or 40% by wt) was reached. To investigate the influence of leachate, solid waste components were also tested after addition of leachate following a similar procedure to reach the required percentage of leachate content (10%, 20%, 30%, or 40% by wt). Leachate was collected from Orange County landfill, Florida, USA. Chemical analysis of the leachate is presented in Table 4.2. All tests were performed in triplicate.

### ***Methodology***

This work focused on spontaneous ignition of solid waste under slow heating depicting temperature rise in the landfill during biological degradation and chemical oxidation. Tests were performed using a programmable furnace that increases the temperature inside the furnace chamber gradually from ambient temperature to beyond ignition. Temperature was increased at a rate of 3°C/min and the test was stopped at ignition or 500°C, the auto-ignition temperature (AIT) for methane (Glassman, 1996), a gas produced from anaerobic biological degradation of waste in landfills.

Spontaneous ignition was observed regularly in coal mines and storage facilities and piles of plastic, dust, and tires. Previous studies of coal combustion (Sujanti et al, 1999; Hill and

Quintiere, 2000, Kadioglu and Varamaz, 2002, Schmidt et al, 2003, Kucuk et al, 2003, Lu et al, 2004 and Vantelon et al, 2005) used the crossing-point method to determine the AIT for the material under study. In the crossing-point method the sample is heated gradually in a furnace from ambient room temperature to ignition, during which the temperature of the sample is monitored. In some studies, AIT was identified as the temperature at which no heat transfer occurred between the surface and the center of the sample and in some other studies AIT was the temperature at which the sample temperature equaled the temperature of the furnace. The crossing-point method was adopted in this study to determine the AIT for various components of solid waste. While solid waste samples were subjected to a gradual temperature increase, temperatures were monitored at the surface and at the center. The AIT was determined as the point of equal temperature between the surface and the center of the sample.

Although, AIT was used extensively, it does not provide adequate information regarding self-heating during temperature rise. Hence, to investigate the thermal behavior during the temperature gradual increase, three points were identified in addition to the AIT on the sample surface and center temperature profiles, shown in Figure 4.2. These points include: the self-heating inflection point temperature ( $T_{S-H}$ ), the center ignition startup temperature ( $C_{ig}$ ), and the surface ignition startup temperature ( $S_{ig}$ ).

Each of these temperatures represents an important point regarding spontaneous combustion. The self-heating inflection point is defined as the temperature at the center with maximum difference between the surface temperature and the center temperature. At this point heat from the chemical exothermic reactions exceeds the furnace heat input. Ignition startup is defined as the

temperature at which the temperature increase in the material changes from linear to exponential rise and is followed by waste material combustion. These four points were determined for the samples and used to compare the different solid waste components under different test conditions. It is worth mentioning that unlike AIT which it is determined as the crossing point, the remaining characteristic temperatures were subjectively determined. Accordingly, these characteristic temperatures are less accurate.

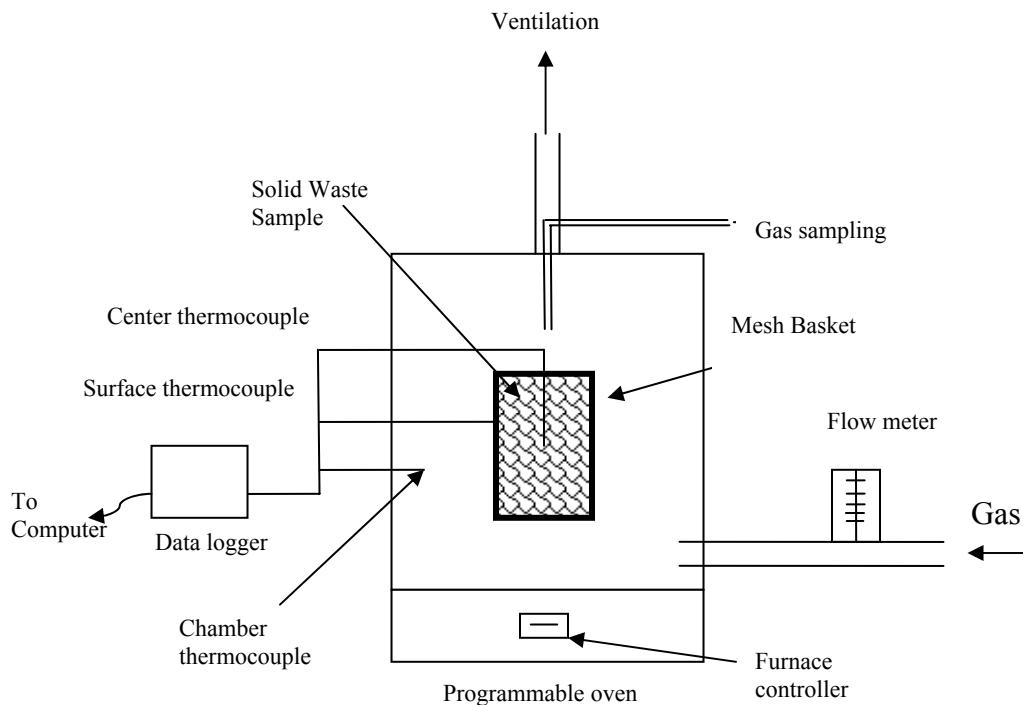


Figure 4.1: Experimental System Setup

Table 4.1: Solid waste components preparation, as received energy content and test observations

Solid waste component	Preparation	Tested Weight (g)	Energy Content (kJ/kg)	Test Observation
Cardboard	Cut to less than 2.5cm	70	16280	Burned completely and created ash
Food (pet food)	No special preparation	230	4650	Need high temperature to burn. Created char at the outside and ash at the center
Yard waste (mulch) and Wood	Cut to less than 2.5cm	155-175	18600	Burned completely and created ash
Glossy paper	Shredded to 7mm x 25-50mm	50	12200	Created char.
Newspaper	Shredded to 7mm x 25-50mm	50	18600	Burned completely and created ash
Office paper	Shredded to 7mm x 25-50mm	50	16750	Burned completely and created ash
Textile (Cotton)	Cut to less than 2.5cm	115-185	17440	Need high temperature to ignite. Created char and ash
Textile (Wool)	Cut to less than 2.5cm	115-185		Need high temperature to ignite. Melted and created little char
Textile (Blend)	Cut to less than 2.5cm	115-185		Need high temperature to ignite. Melted and created char
Plastic	Cut to less than 2.5cm		32560	Collapsed and melted before burning
MSW	Cut to less than 2.5cm	80	11630	Created ash and char. Partially melted.

Table 4.2: Leachate constituent data (From Orange County Landfill)

Parameter*	Unit	Concentration
Arsenic (As)	mg/L	0.057 - 0.12
Benzoic Acid	ug/L	< 5.04
BOD	mg/L	245 - 1010
Boron (B)	mg/L	1.2 - 6.1
Chloride (Cl)	mg/L	304 - 1310
Chromium (Cr)	mg/L	0.028 - 0.15
Cobalt (Co)	mg/L	0.0025 - 0.023
Copper (Cu)	mg/L	0.0065 - 0.018
Cyanide (CN)	mg/L	0.2 - 0.8
Lithium (Li)	mg/L	0.0063 - 0.024
Manganese (Mn)	mg/L	0.29 - 0.4
Molybdenum (Mo)	mg/L	0.0084 - 0.0090
Nickel (Ni)	mg/L	0.019 - 0.11
Nitrogen (N)	mg/L	201 – 822
Oil & Grease	mg/L	17 - 33
pH	-	6.56 - 7.58
Total Phenolics	mg/L	1.25 – 6.14
Phosphorous (P)	mg/L	2.21 – 5.08
Sodium (Na)	mg/L	248 – 1090
Zinc (Zn)	mg/L	0.05 - 0.41

\* Be, Cd, Pb, Hg, and Ag were present at concentrations less than 1 µg/L.

## Results and discussion

### *Temperature profile*

A typical plot of temperature over time during combustion testing is presented in Figure 4.2.

Generally, furnace temperature increased linearly with time (3°C/min), although on rare occasions it was influenced by the sample burning. The temperature profile for the sample surface was curvilinear with three distinct stages, shown in Figure 4.2, (1) a brief warming curve

starting from ambient temperature, (2) a linear increase as the sample is heated by the furnace, then (3) an exponential temperature increase as the temperature at the center becomes higher than at the surface or when sample surface ignited, followed by sample burning and collapse.

Generally, temperature at the sample center initially increased at a very slow rate during the furnace heating. Then, temperature increased linearly up to around 60-70°C at a rate lower than that noted for surface temperature. Next, the temperature at the center tended to level due to a decline in the net heat generation rate. This decrease in net heat generation is believed to be caused by heat absorbed by organic compounds volatilization and water evaporation (Chen and Chong, 1995). After a period of time, temperature again began increasing linearly at a rate greater than the surface heating rate. During the transition from reduced net heat generation to high heat generation, it is assumed that chemical self-heating reactions becomes significant compared to furnace heating. Therefore,  $T_{S-H}$  was considered as the temperature at which the chemical self-heating prevails. As temperature increased linearly at the center after passing  $T_{S-H}$ , the temperature profile undertook an exponential shape indicating ignition initiation followed by burning of the sample.

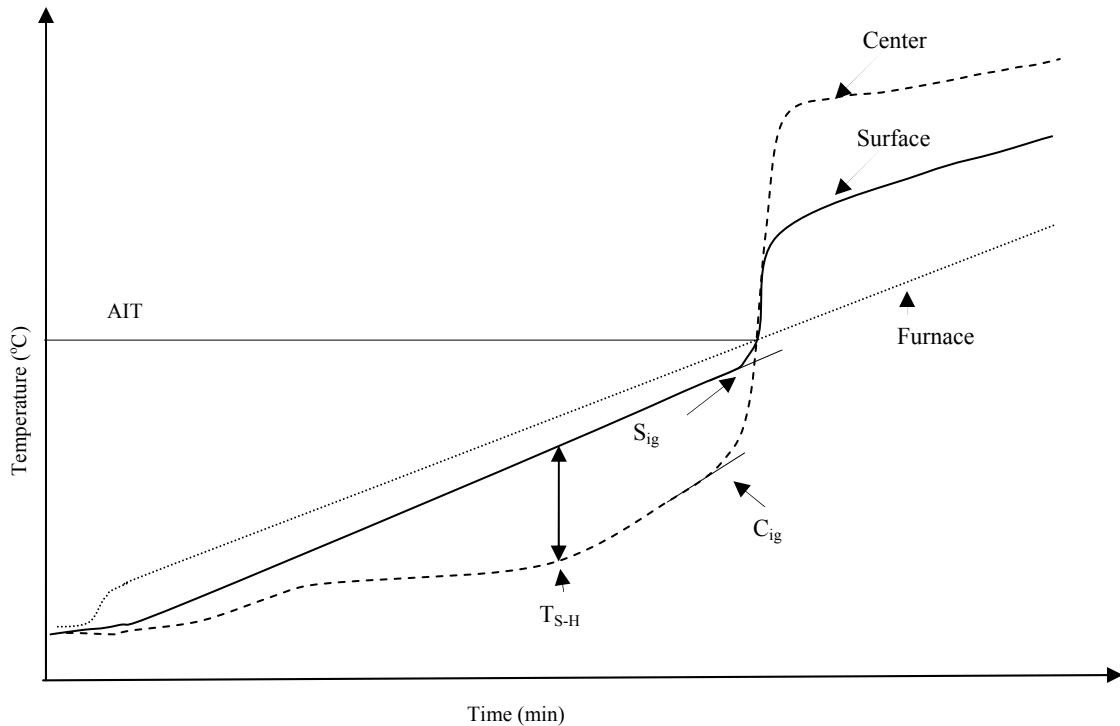


Figure 4.2: Typical Temperature Profiles and Characteristics Points

$C_{ig}$  &  $S_{ig}$  are the temperatures at which the temperature profile changes from linear to exponential.  $T_{S-H}$  is the self-heating inflection point defined as the temperature at the center with maximum difference between the surface temperature and the center temperature.

### ***Solid Waste Components***

Solid waste components were initially tested in dry conditions to exclude the effect of moisture. Characteristic temperatures for dry samples are presented in Table 4.3. The results from the tests showed significant differences among the solid waste components. General notes on solid waste components behavior under slow heating are presented in Table 4.1. Plastic was tested, however results were not presented. Plastics have low melting point, samples melted and collapsed before the test completion. The correlation of characteristic temperatures with sample specific weight,

total energy (J), and specific energy of the samples (J/kg) was examined as well as among the four characteristic temperatures. Significant correlations are reported below.

Comparing the self-heating inflection points for the different components shows a narrow temperature range (111-134°C) except for food (223°C) and cotton textile (181°C). The  $T_{S-H}$  for MSW is found in the middle of this narrow range. Regression correlations were investigated between  $T_{S-H}$  and the different material properties. A relatively strong linear fit model was obtained between  $T_{S-H}$  and the energy content of the sample and the sample specific weight. Equation 4.1 shows correlation obtained and the correlation coefficient of determination.

$$T_{S-H} = 0.327\rho + 83.9 \quad R^2=0.76 \quad (4.1)$$

Where:  $\rho$  is the specific weight the sample ( $\text{kg/m}^3$ ). The correlation suggests a direct relationship between  $T_{S-H}$  and the specific weight and an inverse relationship between  $T_{S-H}$ . The direct relationship between  $T_{S-H}$  and the specific weight might be explained by the fact that higher mass content requires higher energy input to increase the material temperature. The relatively low correlation factor suggests that  $T_{S-H}$  is a function of other factors that are difficult to quantify.

Following the temperature profiles for the sample center, ignition startup temperature ( $C_{ig}$ ) can be considered as the first stage of spontaneous ignition. Solid waste components showed wide variations in this temperature (181-300 °C). MSW was found to have an ignition initiation point near the lower end of waste components tested (200°C). Blended textiles and mulch had the lowest temperature of ignition initiation, 181 and 198 °C respectively. Considering  $C_{ig}$  for solid

waste components, results imply that as temperatures increase toward ignition inside the landfill, textiles may initiate spontaneous combustion of solid waste in the landfill.

Surface ignition startup temperature for the various components showed a wide range of temperatures (217-288 °C), while MSW  $S_{ig}$  was in the lower part of this range (232°C). Surface ignition startup temperatures ( $S_{ig}$ ) were generally higher than the center temperatures except for food and cotton textile which also had the highest specific weight. Higher temperatures for ignition at the surface can be explained by the fact that the number of reacting particles obtaining the required energy to continue the combustion reactions becomes less in open space environment and with air currents; therefore, higher energy input or temperature is needed compared to a confined environment.

No strong correlations could be reached between  $C_{ig}$  or  $S_{ig}$  and specific weight, total energy or specific energy content suggesting startup ignition temperature is subject to collective effect of other parameters that are difficult to quantify.

The AIT for each component and for MSW varied from 204 to 431°C. AITs for paper and cardboard were found in the lower part of this range, while MSW had an average AIT value. A linear correlation was found between the sample specific weight and the AIT. Equations 4.2 and 4.3 show the correlations and the coefficients of determination.

$$AIT = 0.762\rho + 167.1 \quad R^2 = 0.89 \quad (4.2)$$

$$AIT = 0.7639\rho + 3.376 \times 10^{-6} EC + 112.9, \quad R^2 = 0.91 \quad (4.3)$$

Where: EC is the specific energy content (J/kg). Similar to  $T_{S-H}$  correlation, higher mass content requires higher energy input to increase the material temperature which gives higher AIT. Also, the correlation indicates that AIT is affected by the specific energy content. Correlations 4.2 and 4.3 indicate that AIT depends to a large degree on the material specific weight and compaction. However correlation between AIT and specific weight does not suggest cause and effect relation. Including the specific energy increase the accuracy for predicting AIT.

### ***Effect of Moisture Content on Spontaneous Combustion***

The impact of moisture content was investigated by comparing thermal behavior of samples with moisture content of 0, 10, 20, 30, and 40 %, by weight on a dry basis, for each component of the solid waste under the same oxidation conditions. Results are presented in Tables 4.4 through 4.7 and Figures 4.3 through 4.10. The presence of moisture had significant effect but there was no apparent trend as the moisture content increased for all of the solid waste components, therefore, data are collectively presented in frequency plots 4.7 though 4.10.

Compared to dry conditions, the results show that addition of DI water led to a significant increase in AIT except for food and mulch, where auto-ignition temperatures were the same or lower (See Table 4.4 and Figure 4.3). Figure 4.7 shows cumulative distribution of total wet samples for percentage change in AIT. Over 90% of tests found AIT increased with the addition of moisture.

The addition of DI water resulted in a noticeable decrease in self-heating temperatures and center ignition temperatures as shown in Table 4.5 and Figure 4.4. About 82% of tests found  $T_{S-H}$  decreased with the addition of moisture (see Figure 4.8). High specific heat capacity of water and latent heat of evaporation absorbs a significant part of the heat generated; therefore, lower self-heating temperature would be expected.

$C_{ig}$  decreased with the addition of moisture in about 71% of the tests (See Figure 4.9). Decrease in  $C_{ig}$  may be due to the role water vapor plays in accelerating solid waste oxidation. Table 4.6 and Figure 4.5 show experimental results for  $C_{ig}$  at different moisture contents. Literature suggests that the presence of water vapor accelerates ignition because of an increased number of successful collisions between reacting particles as well as the formation of OH radicals which catalyze the combustion process (Glassman, 1996). However, excessive water concentration has a suppressing effect by diluting the particle concentration and therefore the number of successful collisions between particles, reducing the amount of energy available for reacting particles to overcome the activation energy (Glassman, 1996).

Addition of moisture minimally affected ignition temperatures at the surface (see Table 4.7 and Figures 4.6 & 4.10), perhaps due to the experimental conditions where the surface is exposed to direct heating and air currents inside the furnace which rapidly dry the sample surface and reduce the concentration of water vapor close to the sample surface. On the other hand, presence of moisture absorbed heat from the sample and caused the curve to shift to the right and AIT occurred at higher temperature. It indicate that greater energy is needed for the center to reach the surface temperature

Regression correlations were investigated between the characteristic temperature at the different moisture contents tested and moisture content, specific weight, specific energy content, or energy released from the entire sample. No strong correlations were found.

Table 4.3: Dry solid waste components in saturated air <sup>a</sup>

SW component	AIT	T <sub>S-H</sub>	C <sub>ig</sub>	S <sub>ig</sub>
Cardboard	232	124	215	226
Food	396	223	300	254
Mulch	293	127	198	225
Glossy paper	204	120	229	235
Newspaper	241	117	218	229
Office paper	236	111	238	259
Textile (Cotton)	431	181	290	270
Textile (Wool)	329	131	271	288
Textile (Blend)	334	134	181	217
MSW	267	126	200	232

<sup>a</sup> All results are in (°C)

Table 4.4: Results for AIT under different moisture and leachate content <sup>a</sup>

SW Components	Dry	DI, % by wt				Leachate, % by wt			
		10%	20%	30%	40%	10%	20%	30%	40%
Cardboard	232	356	340	380	N/T	287	323	N/T	N/T
Food	396	385	394	N/T	N/T	397	411	N/T	N/T
Mulch	293	250	295	333	N/T	249	270	372	N/T
Glossy paper	204	223	250	298	310	273	258	289	313
Newspaper	241	260	330	358	371	333	332	309	349
Office paper	236	257	268	335	348	236	301	330	397
Textile (Cotton)	431	447	438	N/T	N/T	435	444	N/T	N/T
Textile (Wool)	329	414	375	N/T	N/T	363	378	N/T	N/T
Textile (Blend)	334	356	400	N/T	N/T	360	370	N/T	N/T
MSW	267	392	355	N/T	N/T	299	372	N/T	N/T

N/T: No test was made

<sup>a</sup> All results are in (°C) and average of 3 measurement

Table 4.5: Results for  $T_{S-H}$  under different moisture and leachate content<sup>a</sup>

SW Components	Dry	DI, % by wt				Leachate, % by wt			
		10%	20%	30%	40%	10%	20%	30%	40%
Cardboard	124	108	106	96	N/T	92	103	N/T	N/T
Food	223	150	140	N/T	N/T	154	168	N/T	N/T
Mulch	127	102	84	76	N/T	97	85	106	N/T
Glossy paper	120	96	111	113	105	101	98	118	106
Newspaper	117	126	142	154	115	229	98	99	103
Office paper	111	96	110	125	143	116	93	91	99
Textile (Cotton)	181	98	114	N/T	N/T	107	111	N/T	N/T
Textile (Wool)	131	92	117	N/T	N/T	93	98	N/T	N/T
Textile (Blend)	134	94	103	N/T	N/T	81	99	N/T	N/T
MSW	126	96	108	N/T	N/T	102	97	N/T	N/T

N/T: No test was made

<sup>a</sup> All results are in (°C) and average of 3 measurement

Table 4.6: Results for  $C_{ig}$  under different moisture and leachate contents<sup>a</sup>

SW Components	Dry	DI, % by wt				Leachate, % by wt			
		10%	20%	30%	40%	10%	20%	30%	40%
Cardboard	215	211	178	139	N/T	202	199	N/T	N/T
Food	300	193	221	N/T	N/T	226	205	N/T	N/T
Mulch	198	212	190	174	N/T	207	194	173	N/T
Glossy paper	229	184	177	169	96	226	163	186	128
Newspaper	218	224	215	287	197	235	252	153	166
Office paper	238	252	220	167	163	249	151	205	108
Textile (Cotton)	290	332	335	N/T	N/T	265	340	N/T	N/T
Textile (Wool)	271	177	148	N/T	N/T	195	161	N/T	N/T
Textile (Blend)	181	195	143	N/T	N/T	136	183	N/T	N/T
MSW	200	210	179	N/T	N/T	241	192	N/T	N/T

N/T: No test was made

<sup>a</sup> All results are in (°C) and average of 3 measurement

Table 4.7: Results for  $S_{ig}$  under different moisture and leachate contents <sup>a</sup>

SW Components	DI, % by wt					Leachate, % by wt			
	Dry	10%	20%	30%	40%	10%	20%	30%	40%
Cardboard	226	226	236	245	N/T	231	223	N/T	N/T
Food	254	314	291	N/T	N/T	313	287	N/T	N/T
Mulch	225	222	232	230	N/T	222	224	217	N/T
Glossy paper	235	*	240	240	254	240	248	259	238
Newspaper	229	236	277	249	251	*	237	241	250
Office paper	259	258	263	255	259	249	251	255	254
Textile (Cotton)	270	272	274	N/T	N/T	265	265	N/T	N/T
Textile (Wool)	288	250	237	N/T	N/T	239	234	N/T	N/T
Textile (Blend)	217	204	222	N/T	N/T	226	227	N/T	N/T
MSW	232	241	233	N/T	N/T	244	234	N/T	N/T

N/T: No test was made

\* Furnace was turned off before combustion

<sup>a</sup> All results are in (°C) and average of 3 measurement

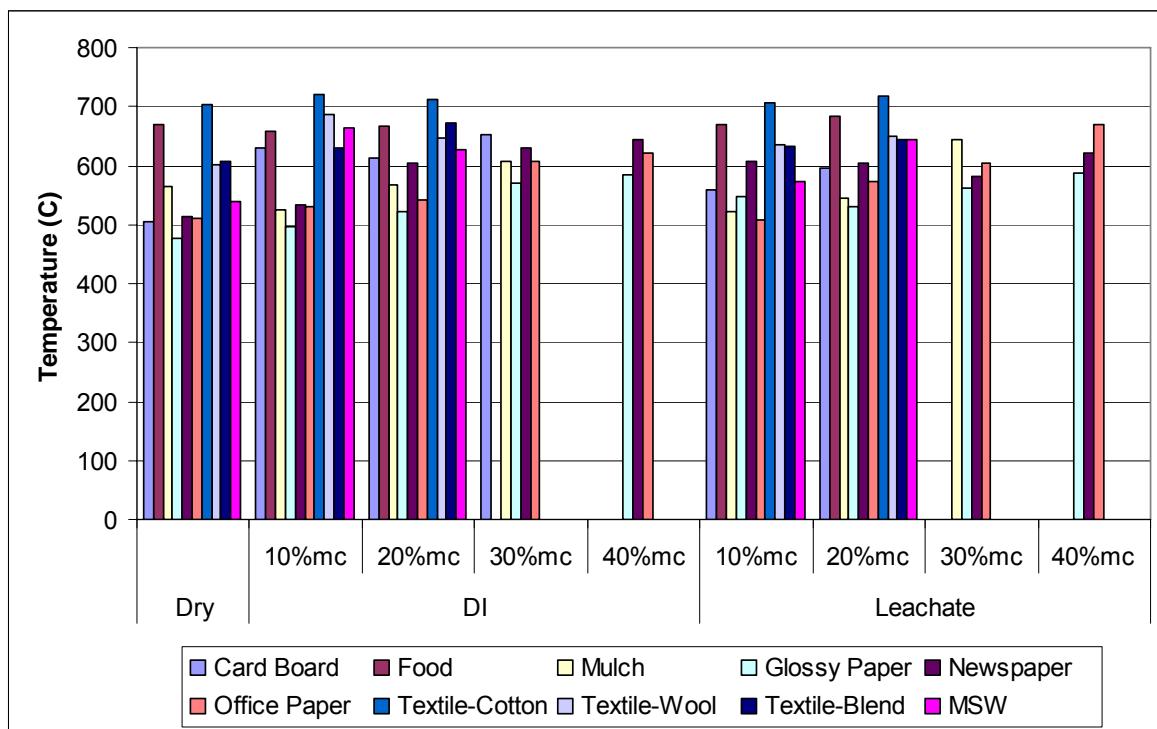


Figure 4.3: Graphical presentation of AIT (in °C) under different moisture and leachate content

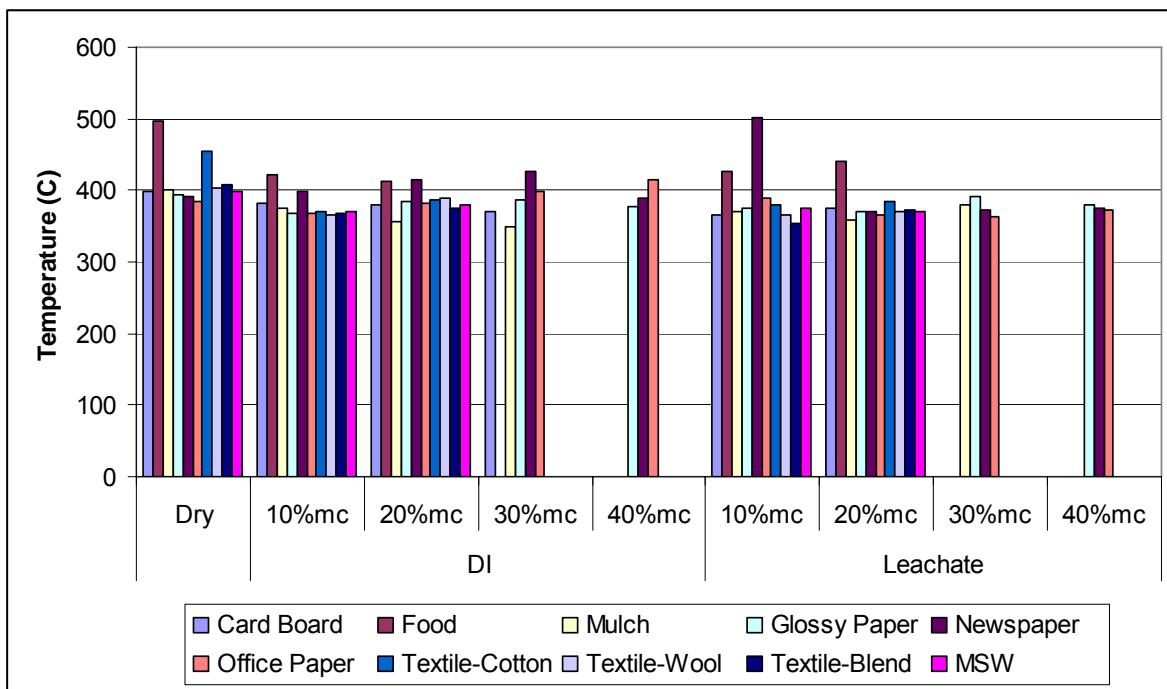


Figure 4.4: Graphical presentation of  $T_{S-H}$  (in  $^{\circ}\text{C}$ ) under different moisture and leachate content

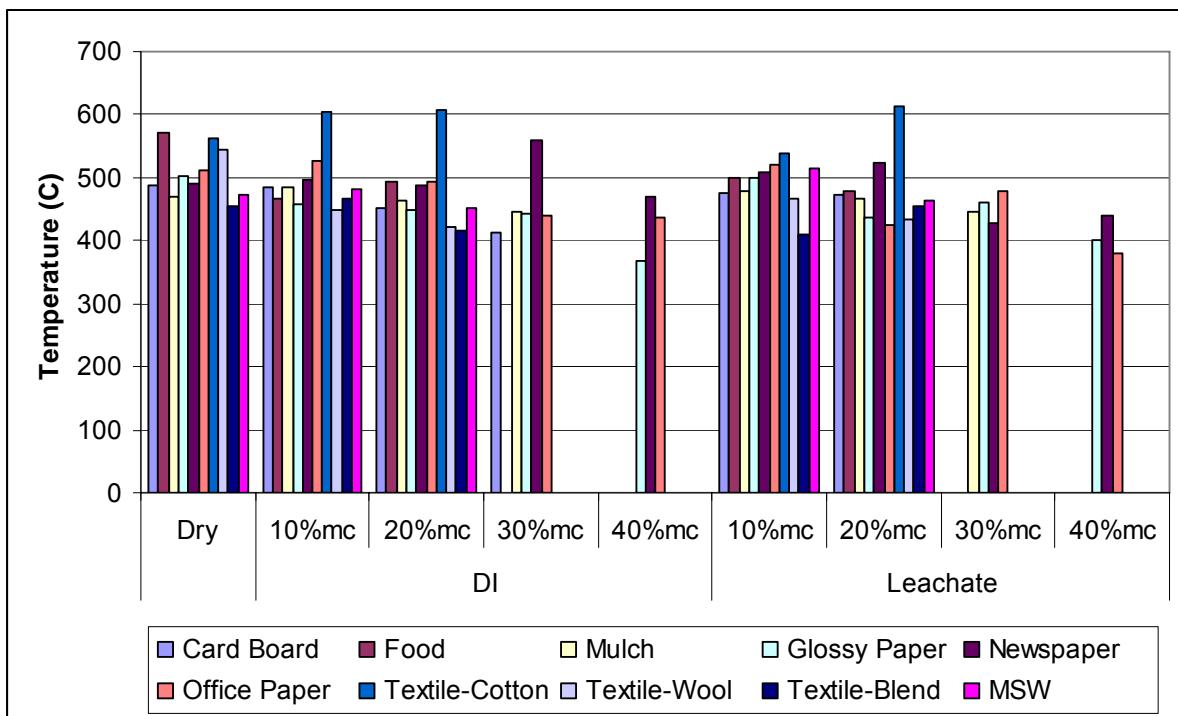


Figure 4.5: Graphical presentation of  $C_{ig}$  (in  $^{\circ}\text{C}$ ) under different moisture and leachate content

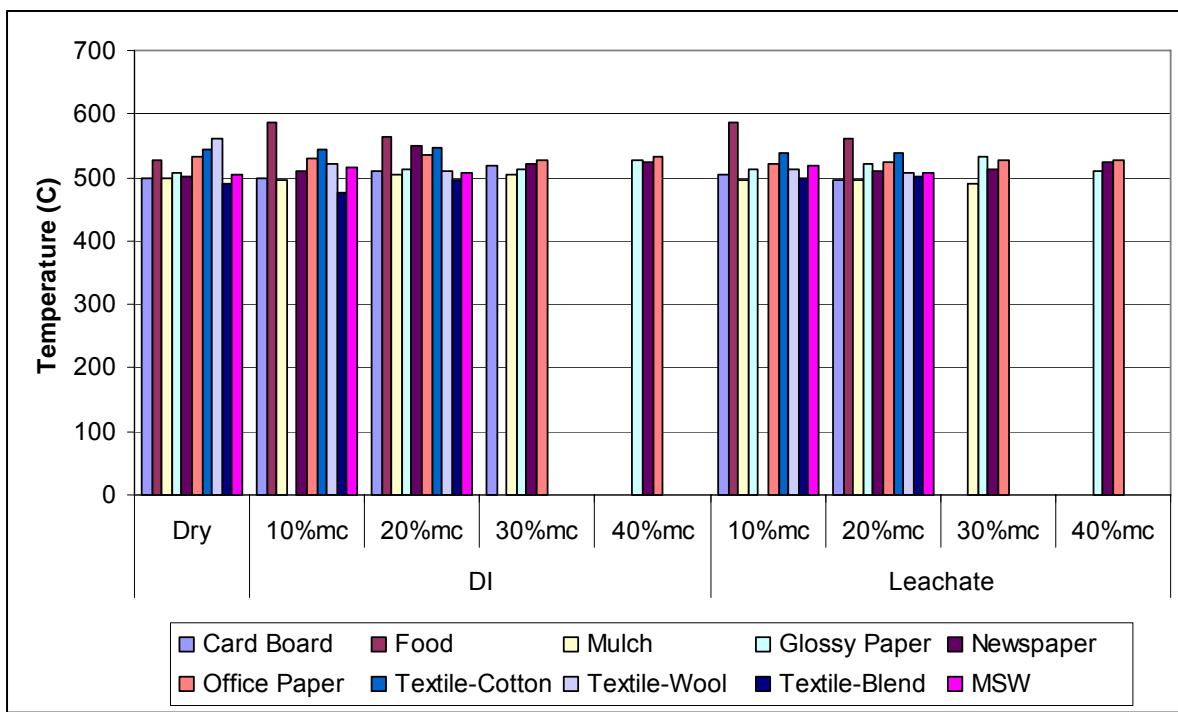


Figure 4.6: Graphical presentation of  $S_{ig}$  (in °C) under different moisture and leachate content

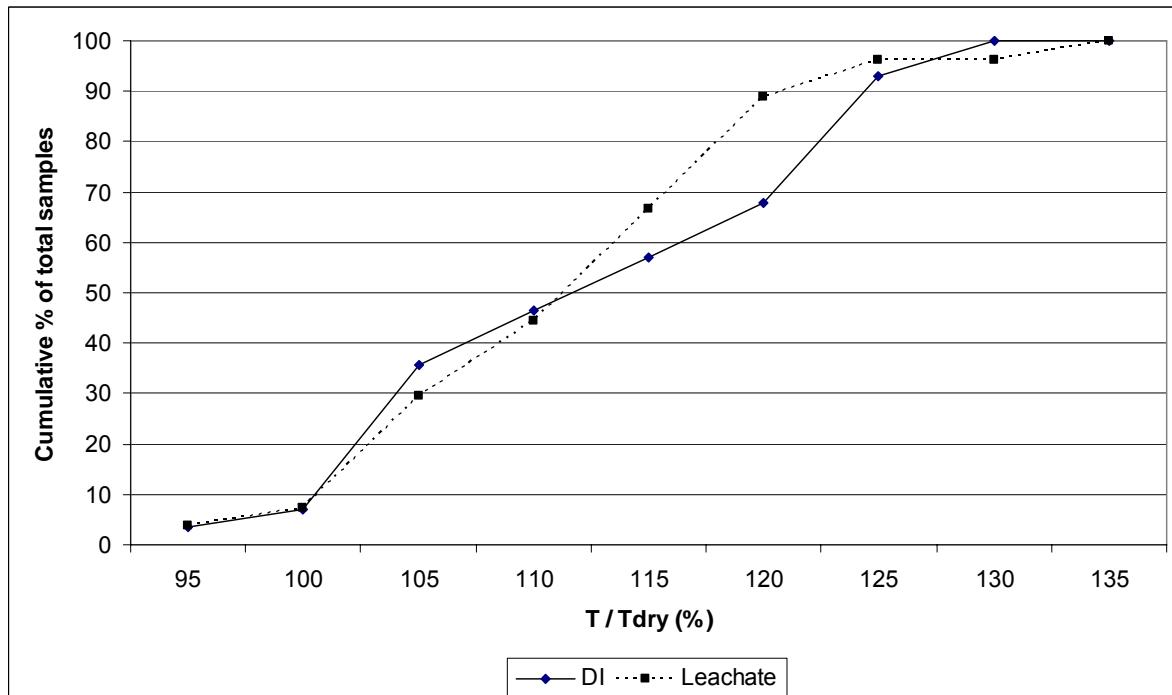


Figure 4.7: Cumulative Distribution of Wet Samples (all liquid contents) for AIT (in °K) compared to Dry Samples.

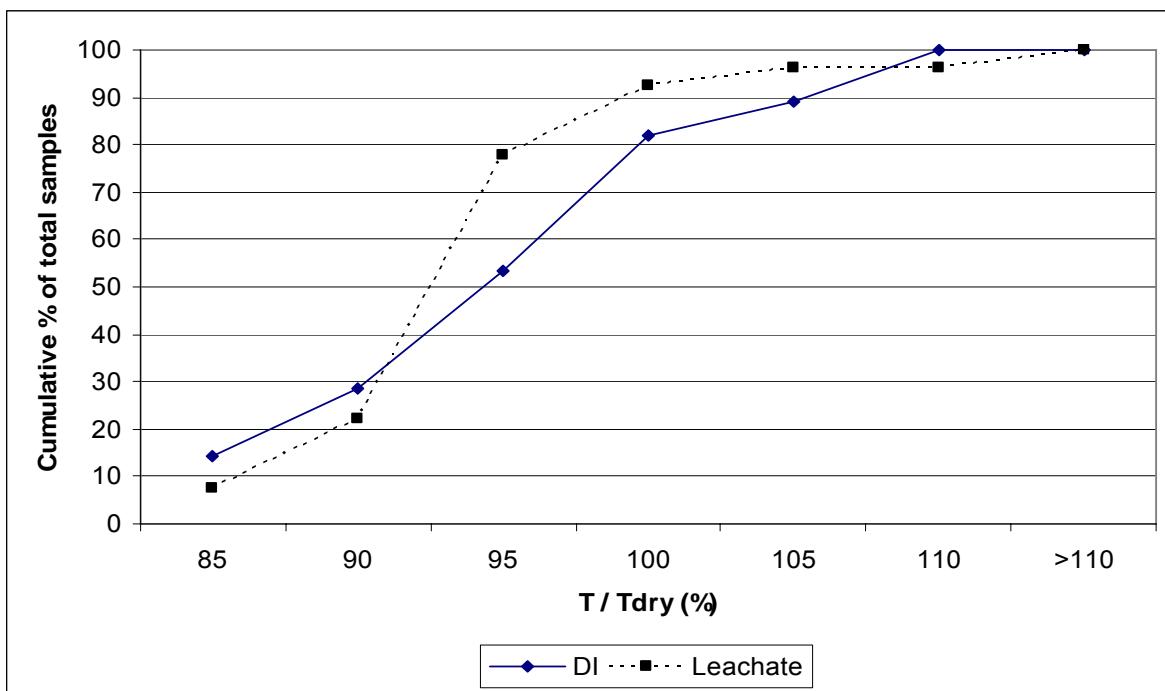


Figure 4.8: Cumulative Distribution of Wet Samples (all liquid contents) for  $T_{S-H}$  (in  $^{\circ}\text{K}$ ) compared to Dry Samples.

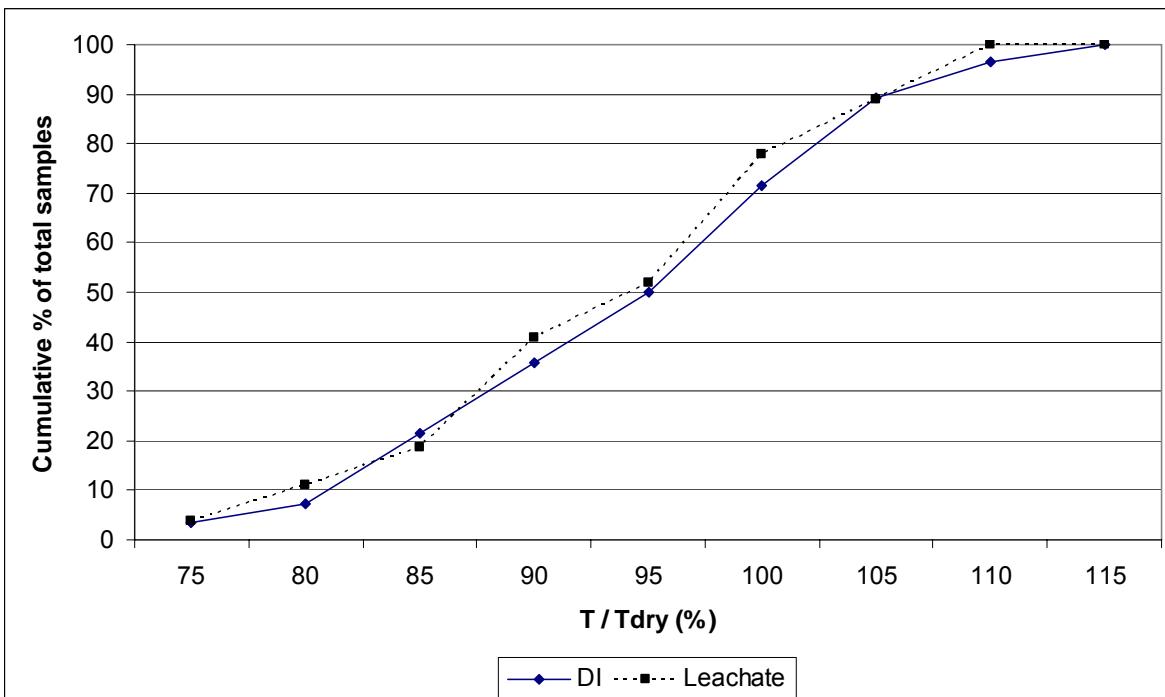


Figure 4.9: Cumulative Distribution of Wet Samples (all liquid contents) for  $C_{ig}$  (in  $^{\circ}\text{K}$ ) compared to Dry Samples.

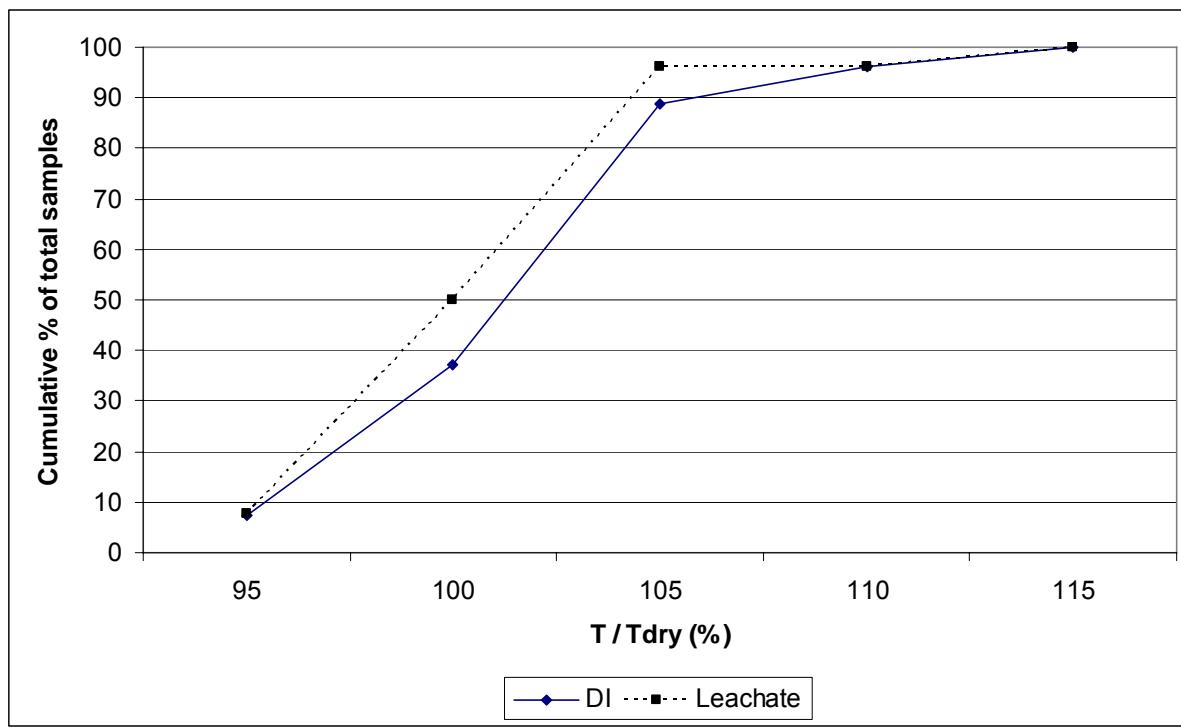


Figure 4.10: Cumulative Distribution of Wet Samples (all liquid contents) for  $S_{ig}$  (in  $^{\circ}\text{K}$ ) compared to Dry Samples.

#### ***Effect of Leachate on Spontaneous Combustion***

The effect of leachate on combustion was investigated in a similar way to the moisture content tests. Solid waste components and MSW samples were prepared with 10, 20, 30, and 40 %, by weight on a dry basis, of leachate. Results are presented in Tables 4.4 through 4.7 and Figures 4.3 through 4.10. The presence of leachate had significant effect but there was no apparent trend as the leachate content increased, therefore, data are collectively presented in frequency plots 4.7 through 4.10.

Compared to dry tests, leachate increased the AIT significantly for solid waste components, except for mulch where AIT was lower than both dry samples and samples with added DI water.

Addition of leachate lowered the self-heating temperature and center ignition startup temperatures significantly for 93% and 78% of the tests, respectively (see Figures 4.8 and 4.9). Surface ignition startup had minimal effect from moisture as seen in Figure 4.10. However, dissolved solids decreased  $S_{ig}$  relatively more than in samples with DI-water. Comparing results from leachate tests and DI-water tests, results suggest that leachate promoted chemical oxidation more than DI-water.

Literature reported that some salts or metal compounds exhibit smoldering inducing effects (e.g. compounds containing metal cations such as Li, Na, K, Rb, Cs, Ag, Fe, Cr, or Pb) and some smoldering suppressing effects (e.g. metal chloride), (McCarter, 1977; Sujanti and Zhang, 1999; and Buggeln and Rynk 2002). Some of these compounds, Fe (II and III) and Cr (III) chlorides, can either promote or suppress smoldering and oxidation, depending on their form (for example powdered vs. granular, McCarter, 1977). Walker and Harrison (1977) studied the addition of ferric oxide to sawdust and reported an increase in pyrolysis and oxidation rates. Table 4.2 shows constituents and their concentrations of the leachate used in this experiment. While some compounds found in the leachate tested (Li, Na, Ag, Cr, Cl, and Pb) were found to promote smoldering, the collective influence of these elements is not known. Given that leachate quality changes with time and landfill operation, it is difficult to predict precisely the degree that leachate will affect spontaneous combustion in landfills.

### ***Oxygen concentration***

Tests under different oxidative environment were conducted by injecting the furnace chamber with gas with oxygen concentration of 21% (saturated air), 10%, and 0% by volume. Tests were

conducted for samples with different moisture content (0, 10%, 20%, 30%, and 40%, by weight dry basis). Also, the effect of leachate on combustion at different oxygen levels was investigated. However, the effect of oxygen concentration on dry samples test results are presented here as results of DI-water or leachate effects in lower oxygen environments did not show significant differences from tests in saturated air, results are presented in Tables 4.8 and 4.9.

At 10% by volume oxygen, results showed a slight increase in AIT for solid waste components except for the cotton textile, while AIT for MSW was the same when compared to air. Self-heating at the center was observed suggesting that oxygen concentration as low as 10% can sustain chemical oxidation. The  $T_{S-H}$  points were slightly lower than air tests except for cotton textile, which was significantly lower.  $C_{ig}$  and  $S_{ig}$  were within 10% of their respective values in air except for food and wool. MSW required slightly higher temperature for ignition startup than in air. Generally, at 10% by volume oxygen, thermal runaway did not occur after temperature passed  $C_{ig}$  or  $S_{ig}$ . Smoldering was observed for all the samples during the test. Samples exhibited flammable combustion as the furnace door was opened and air flowed into the furnace chamber.

Heat generation due to exothermic pyrolysis occurred in tests at 0% by volume oxygen. Results indicated a general decrease in self-heating temperature and significant increase in the remaining characteristic points compared to tests in air and 10% by volume oxygen. A decrease in self-heating suggests a significant heat generation from exothermic pyrolysis in the absence of oxygen. A decrease in self-heating temperature in 10% and 0% by volume oxygen compared to air indicates a higher net heat generation rate in low oxygen environment than in air at the

beginning of material volatilization. Once chemical self-heating started, the chemical oxidation proceeds to ignition faster than pyrolysis leading to lower AIT, C<sub>ig</sub>, and S<sub>ig</sub>. Similar to tests in 10% by volume oxygen, samples did not burn due to the lack of oxygen. However, samples continued to disintegrate, leaving only char.

Table 4.8: Characteristic Temperature for dry solid waste at 10% Oxygen

SW component	AIT	T <sub>S-H</sub>	C <sub>ig</sub>	S <sub>ig</sub>
Cardboard	263	115	205	247
Food	399	197	226	247
Mulch	292	124	203	213
Glossy paper	239	133	229	245
Newspaper	245	126	216	243
Office paper	274	101	253	274
Textile (Cotton)	403	135	322	278
Textile (Wool)	359	140	232	246
Textile (Blend)	*	*	*	*
MSW	265	122	218	247

\* Not tested

<sup>a</sup> All results are in (°C) and average of 3 measurement

Table 4.9: Characteristic temperatures for dry solid waste at 0% oxygen.

SW component	AIT	T <sub>S-H</sub>	C <sub>ig</sub>	S <sub>ig</sub>
Cardboard	345	112	252	**
Food	**	234	**	**
Mulch	314	99	246	239
Glossy paper	338	89	325	334
Newspaper	359	95	242	346
Office paper	338	95	277	293
Textile (Cotton)	460	330	330	340
Textile (Wool)	459	97	312	**
Textile (Blend)	*	*	*	*
MSW	396	94	252	264

\* Not tested

\*\* Not detected

<sup>a</sup> All results are in (°C) and average of 3 measurement

## **Conclusions**

Few studies have been conducted on spontaneous fires in landfills. To date little information has been presented regarding the thermal behavior of solid waste and measurements of spontaneous ignition of solid waste have not been made. In this study spontaneous combustion in municipal solid waste was investigated. Laboratory experiments were conducted evaluating the effect of moisture content, oxygen concentration and leachate on spontaneous ignition of solid waste. Also, a comparison was made between solid waste components and synthesized solid waste. The study enabled a better understanding of the self-heating process and spontaneous combustion in landfills. Effects of parameters critical to landfill operation on spontaneous combustion were determined.

Methane often has been suspected to initiate spontaneous subsurface fires in the landfill. However, a combustible mixture of methane and oxygen requires very high temperature to ignite ( $> 500^{\circ}\text{C}$ ). In this study it was shown that spontaneous fires are initiated by solid materials with lower ignition point. The crossing-point method was used to study the spontaneous combustion of solid waste and determine the auto-ignition temperature of the solid waste components and synthesized mixture. In addition, three characteristics temperature points were suggested and used to study and characterize spontaneous combustion of solid waste. These three points and AIT enabled better understanding of self-heating and material behavior during slow heating. Solid waste components tests show a significant variation among the solid waste components during self-heating correlated mainly to specific weight and other difficult to quantify parameters. Correlations have been established between AIT, specific weight and energy content and between self-heating temperature and specific weight which indicate that compaction can help

avoid spontaneous combustion in the landfill. Dense materials require higher energy to increase in temperature and they limit the accessibility of oxygen.

Based on the laboratory experiment, moisture can generally promote both biological and chemical self-heating. Increasing moisture content lowers the solid waste permeability and absorbs more energy as the liquid evaporates. Dissolved solids in leachate were found to promote self-heating and ignition more than distilled water. Tests with varying oxygen concentrations suggested that heat generation occurs due to chemical oxidation even at oxygen concentration as low as 10% by volume. At 10% by volume oxygen, self-heating did not exhibit thermal runaway nor flammable combustion. At 0% by volume oxygen, self-heating occurred due to slow pyrolysis. An increase in temperature caused solid waste to char, creating a weak structure. Also, it was concluded that heat generated from chemical oxidation plays a major role in spontaneous combustion.

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## CHAPTER FIVE

### ENERGY MODELING OF THE SPONTANEOUS COMBUSTION

#### **Introduction**

Determining the conditions favoring spontaneous combustion is critical for landfill operators. However, identifying these conditions requires full understanding of the chemical reactions, landfill operation, and landfill structure. In this part of the study, a simple energy balance model was developed to simulate the heat generation in the landfill. The purpose of this simulation is to better understand heat generation in a landfill and to study the major factors influencing the energy balance and lead to a spontaneous combustion.

#### **Model Description**

A one-dimensional finite-difference model of the temporal distribution of heat inside the landfill was developed using Microsoft Excel 2003. The model was applied to a longitudinal section from a landfill located between the landfill side slope and a vertical gas collection well located 10 m from the side slope, simulating pulling air into a landfill by overdraining on a well. Diagram of the simulated section and unit volume cell is presented in Figure 5.1

The energy balance is represented by Equation 5.1 (El-Fadel et al, 1999):

$$\rho C \frac{\partial T}{\partial t} = k \nabla^2 T + \rho_g C_{pg} v \frac{\partial T}{\partial x} + \Delta H_{Gen} \quad (5.1)$$

Where  $\rho$  is specific weight ( $\text{kg}/\text{m}^3$ ),  $C_p$  is specific heat capacity ( $\text{J}/\text{kg.K}$ ),  $T$  is temperature (K),  $t$  is time (s),  $k$  is the thermal conductivity ( $\text{W}/\text{m.K}$ ),  $\Delta H_{\text{Gen}}$  is the net heat generated ( $\text{J}/\text{m}^3.\text{s}$ ). The term on the left represents energy storage. The first term on the right side represents heat conduction, the second term denotes heat convection and the third term represents heat generation.

Boundary conditions include the following:

$$k \frac{\partial T}{\partial x} = -h(T - T_\infty) \quad t > 0, x = x_0 \quad (5.2)$$

$$\frac{\partial T}{\partial x} = 0 \quad \text{at } x = 0 \quad (5.3)$$

Initial conditions are described below:

$$t = 0, T = T_a$$

Heat generation due to anaerobic degradation was related to methane generation potential as described by Vesilind et al (2003) and EPA (2005). Heat generation equations are provided in Equations 5.4 and 5.5:

$$\Delta H_{an} = Q_{an} D \quad (5.4)$$

$$D = A_{an} L_o M \exp(-A_{an} t) \quad (5.5)$$

Where:  $\Delta H_{an}$  is anaerobic heat generation rate ( $\text{J}/\text{m}^3.\text{s}$ ),  $Q_{an}$  is heat of anaerobic degradation ( $\text{J}/\text{m}^3\text{CH}_4$ ),  $D$  is methane production rate ( $\text{m}^3/\text{s}$ ),  $A_{an}$  is a first order rate constant ( $\text{s}^{-1}$ ),  $L_o$  is

methane generation potential ( $\text{m}^3/\text{kg}$  wet waste),  $M$  is mass of wet waste ( $\text{kg}/\text{m}^3$ ), and  $t$  is time (s)

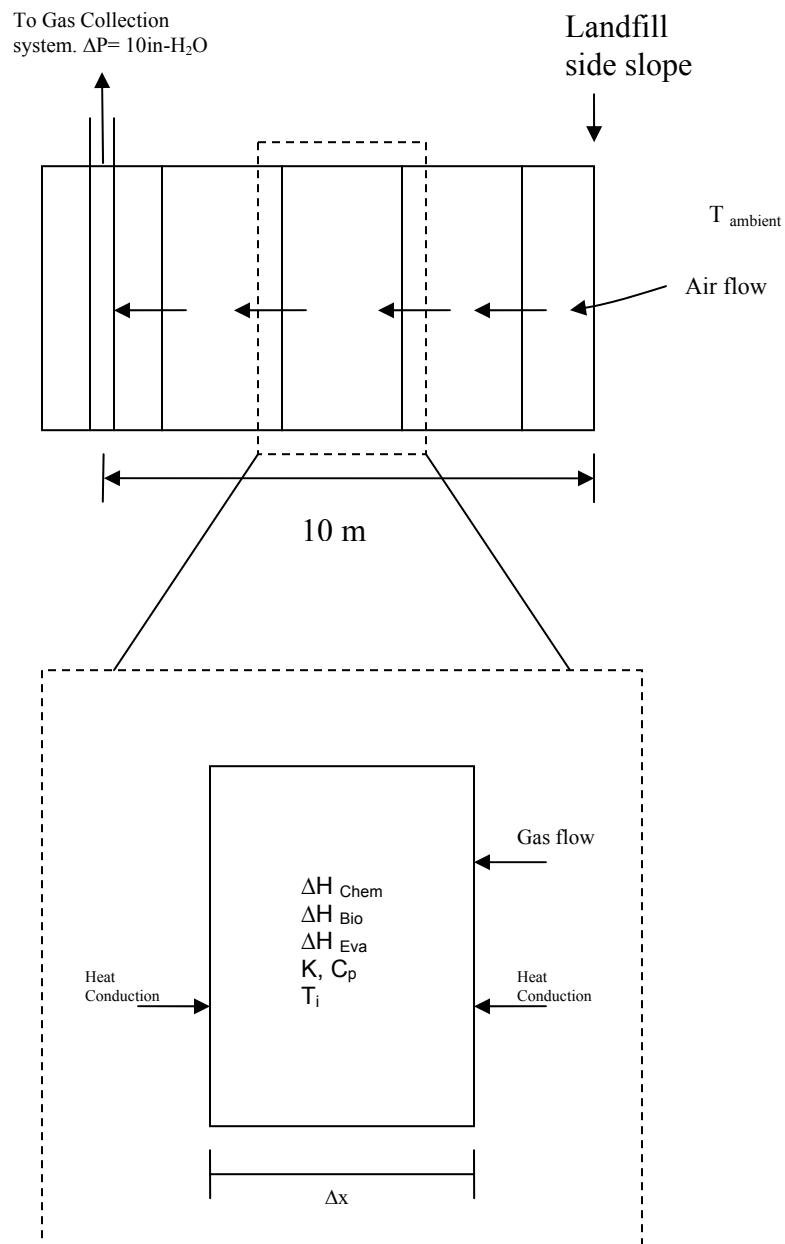


Figure 5.1: Simulated Section Diagram

In this model heat generation from aerobic reaction is expressed by heat released from degradation of glucose ( $C_6H_{12}O_6$ ) as a surrogate substrate as shown in Equation 5.6.

$$\Delta H_{ae} = Q_{ae} \frac{dC_{C_6H_{12}O_6}}{dt} \quad (5.6)$$

The degradation rate of glucose is expressed by Equation 5.7 (Wallner et al 2003):

$$\frac{dC_{C_6H_{12}O_6}}{dt} = \frac{A_1 \exp\left(\frac{-E_{a1}}{RT_s}\right)}{1 + A_2 \exp\left(\frac{-E_{a2}}{RT_s}\right)} C_{C_6H_{12}O_6} y_{O_2} f \quad (5.7)$$

Where:  $\Delta H_{ae}$  is aerobic heat generation rate ( $J/m^3.s$ ),  $Q_{ae}$  is heat of aerobic biological degradation ( $J/kg C_6H_{12}O_6$ ),  $A_1$ ,  $A_2$  are frequency factors ( $s^{-1}$ ,  $-$ ),  $E_{a1}$  is activation energy ( $J/mole$ ),  $E_{a2}$  is activation energy ( $J/mole$ ),  $y_{O_2}$  is oxygen volume percentage,  $f$  is an oxygen consumption coefficient, and  $C_{C_6H_{12}O_6}$  is concentration of glucose ( $kg/m^3$ ).

Further, heat generation due to chemical oxidation is based on the Arrhenius relationship, Equation 5.8:

$$\Delta H_{Ch} = Q_{Ch} \rho A_{Ch} \exp\left(\frac{-E_{Ch}}{RT}\right) \quad (5.8)$$

Where:  $\Delta H_{Ch}$  is chemical heat generation rate ( $J/m^3 \cdot s$ ),  $Q_{Ch}$  is heat of chemical degradation ( $J/kg C_6H_{12}O_6$ ),  $A_{Ch}$  is the frequency factor ( $s^{-1}$ ) and  $E_{Ch}$  is activation energy ( $J/mole$ )

Heat loss due to water evaporation is expressed in Equation 5.9 (Rostami et al, 2003):

$$\Delta H_{Eva} = Q_{Eva} \rho A \exp\left(\frac{-E_{Eva}}{RT}\right) \quad (5.9)$$

Where:  $\Delta H_{Eva}$  is heat loss rate ( $J/m^3 \cdot s$ ),  $Q_{Eva}$  is latent heat of evaporation ( $J/kg H_2O$ ),  $A_{Eva}$  is the frequency factor ( $s^{-1}$ ), and  $E_{Eva}$  is activation energy ( $J/mole$ )

The landfill section was modeled as five CSTRs in series. Several simplifying assumptions were applied to the model. The solid waste was assumed to have a homogeneous composition across the simulated section and the thermal conductivity was constant. The biodegradable material and organic materials were assumed to be 30 % and 80% by weight of the MSW in the landfill, respectively (Tchobanoglous et al, 1993). Air flow through the landfill was assumed to be uniform; however, in reality preferential pathways develop, allowing gas to flow in sections of the landfill faster than others creating local differences in oxygen concentration. Air flow was assumed to be driven by the pressure difference between the gas collection well and the landfill side slope. Pressure gradient was assumed to be  $25 \text{ cm-H}_2\text{O} = 2490 \text{ N/m}^2$  over the entire modeled section (Tchobanoglous, 1993). Solid waste air permeability is assumed to be within the range of  $1.6 \times 10^{-13}$  to  $3.2 \times 10^{-11} \text{ m}^2$  (Jain et al, 2005). Because oxygen is consumed during aerobic degradation of solid waste, oxygen concentration was assumed to decline across the modeled

section starting with 21% by volume at the landfill side slope and reaching 10% by volume at the collection well. Aerobic degradation was assumed to stop at moisture content of 15% by weight, (Fleming, 1991), while anaerobic degradation was assumed to stop at moisture content of 25% by weight (Reinhart and Townsend, 1998). Water evaporation is limited by gas-water equilibrium. Aerobic degradation rates increase up to the lethal temperature limit for microbes. In this model lethal limit for aerobic microbes was assumed to be 65°C (Storm, 1985), while the anaerobic microbe lethal limit was assumed to be 55°C, (Reinhart and Townsend, 1998). Typical values for model input parameters for MSW landfills were obtained from literature, parameters values and their sources are described in Table 5.1.

### **Estimation of Chemical Oxidation Kinetic Parameters**

Literature includes numerous works on heat generation kinetics for aerobic and anaerobic degradation (Yoshida et al, 1999; Lefebvre et al, 2000; Lanini et al 2001; Wallner et al 2003; Yesiller et al ,2005; and Gholamifard et al 2008). On the other hand, chemical oxidation kinetics of solid waste in landfills are rarely found in literature. To estimate these chemical oxidation kinetics, experimental data from laboratory work were used.

The energy balance equation represented by Equation 5.1 was applied to the solid waste samples inside the furnace. Due to the shape of the mesh basket holding the sample, the energy balance equation was applied using cylindrical coordinates. Diagram of the sample simulated is presented in Figure 5.2

$$\rho C \frac{\partial T}{\partial t} = k \nabla^2 T + \rho_s C_{pg} v \frac{\partial T}{\partial r} + \Delta H_{Gen} \quad (5.10)$$

Boundary conditions assumed were:

$$k \frac{\partial T}{\partial r} = -h(T - T_\infty) \quad t > 0, r = r_o \quad (5.11)$$

$$\frac{\partial T}{\partial r} = 0 \quad \text{at } r = 0 \quad (5.12)$$

Initial conditions assumed were:

$$t = 0, T = T_a$$

Where:  $r$  is the radial distance,  $r_o$  is the sample radius,  $T_\infty$  is the furnace temperature, and  $T_a$  is the ambient room temperature.

To estimate the heat generated from the solid waste during gradual heating, simplifying assumptions were made. The temperature profile was assumed to be symmetrical around the center. Also, air inside the furnace was assumed to be completely mixed. Since the air flows around the sample rather than through it, the furnace convective heat loss inside the sample is assumed to be negligible. Accordingly, the second term from the right side of Equation 5.10 was neglected.

The solution for the model was obtained iteratively to determine the values of A and E in Equation 5.8, therefore, values attained are not unique. Different combinations of A and E values can produce very similar temperature profiles. Results from model verification show a good agreement between the data set and simulation as shown in Figure 5.2. Values for A and E for

the chemical heat generation for MSW were found to be 65000 kJ/mole and  $2200 \text{ s}^{-1}$ , respectively.

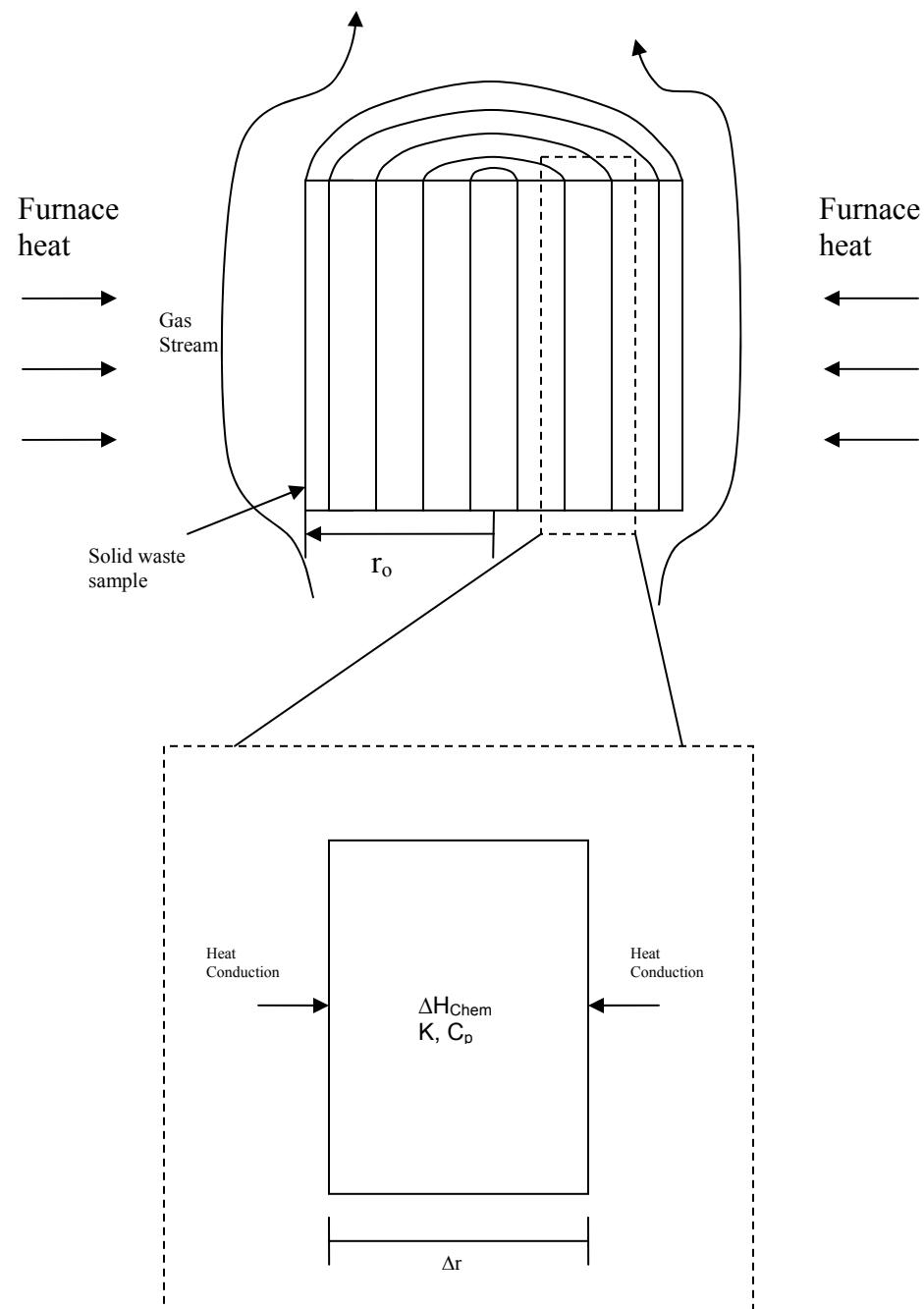


Figure 5.2: Diagram of Experiment Simulation

## **Gas Flow Rate Effect**

Gas flow inside the solid waste has an important role in controlling the landfill temperature. Gas flow rate can control the rate of oxygen supply for microbial and chemical oxidation. Higher gas flow rate results in more oxygen available for the reaction. In this model, an oxygen concentration gradient was assumed across the simulated section; therefore, the effect of gas flow rate on oxygen concentration is not seen. Gas flow rate also controls the rate of moisture evaporation. As the temperature increases, the gas volume and gas saturation limit increase, hence landfill gas holds more water. Temperature profiles of simulated section for different gas flow rates in aerobic condition is presented in Figure 5.4. To distinguish the heat loss of water evaporation from heat loss by convection, contribution of each element to the energy balance was plotted as seen in Figure 5.5. The individual energy plot indicates water evaporation is the major heat sink in the energy balance.

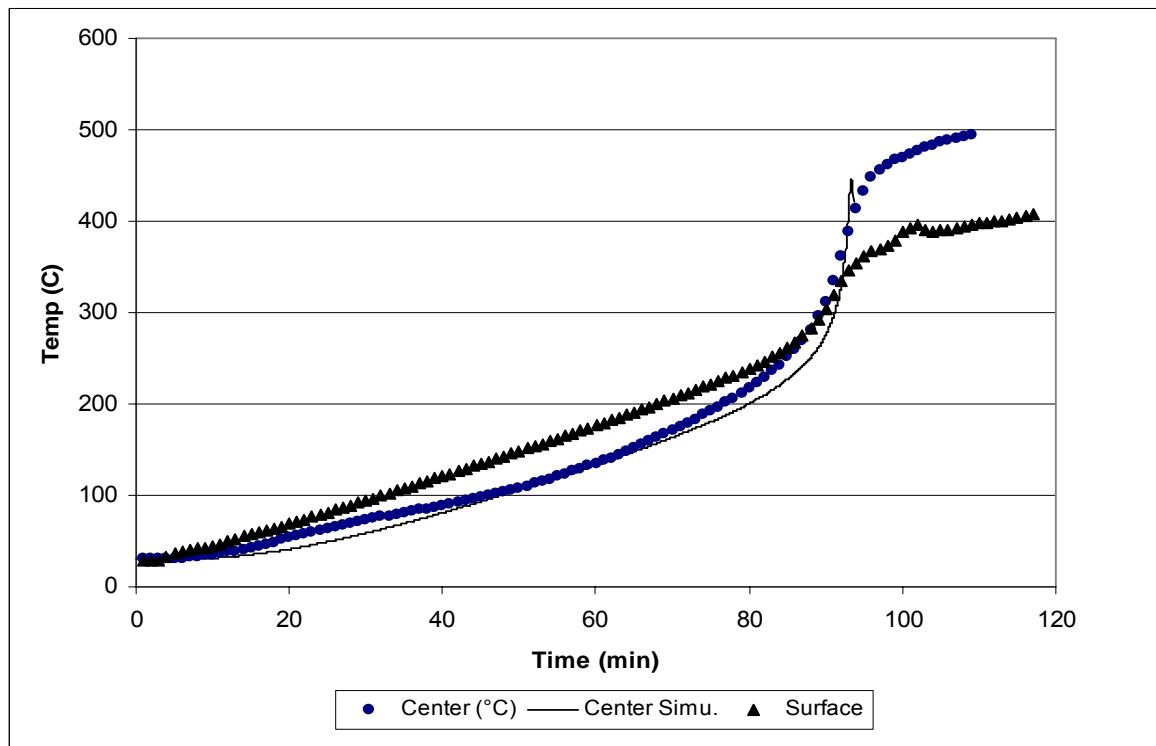


Figure 5.3: Laboratory experiment simulation for dry MSW in air

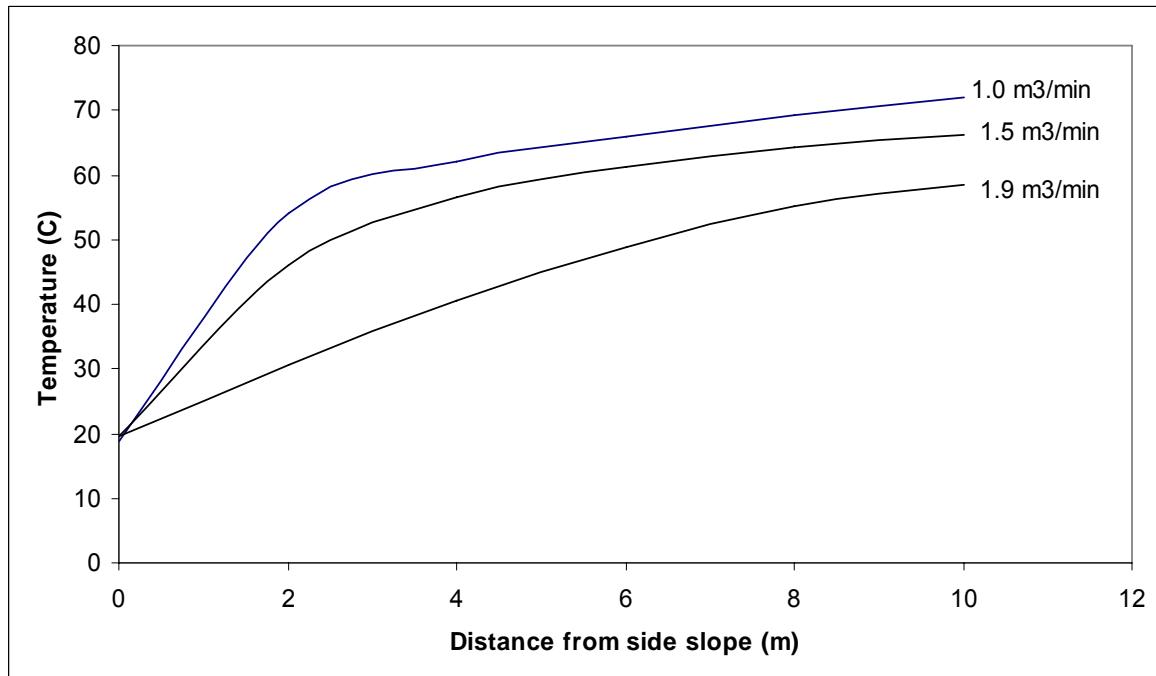


Figure 5.4: Temperature profile of simulated section at different gas flow rates

Table 5.1: Values for solid waste parameters used in model

<b>Parameter</b>	<b>Value</b>	<b>Reference</b>
A <sub>1</sub>	3800 s <sup>-1</sup>	Wallner et al 2003
A <sub>2</sub>	1E45	Wallner et al 2003
A <sub>Ch</sub>	0.15 s <sup>-1</sup>	Experimental
A <sub>an</sub>	0.05 yr <sup>-1</sup>	Vesiland et al, 2002
A <sub>Eva</sub>	2.8x10 <sup>6</sup> s <sup>-1</sup>	Rostami et al, 2003
C <sub>p</sub>	1939 J/kg.K	Yoshida eta al, 1999
C <sub>pg</sub>	1010 J/kg.K	Incropera and Dewitt, 2002
E <sub>1</sub>	38260 J/mol	Wallner et al 2003
E <sub>2</sub>	285204.5 J/mol	Wallner et al 2003
E <sub>Ch</sub>	40000 J/mol	Experimental
E <sub>Eva</sub>	19.5 Kcal/gmol	Rostami et al, 2003
F	0.00141	Wallner et al 2003
H	10 W/m <sup>2</sup> .K	Incropera and Dewitt, 2002
K	0.1 W/m.K	Yesiller et al ,2005
L <sub>o</sub>	0.17 m <sup>3</sup> /Kg wet waste	Vesiland et al, 2002
Q <sub>ae</sub>	14944375 J/kg glucose	Wallner et al 2003
Q <sub>an</sub>	15696 J/ m <sup>3</sup> -CH <sub>4</sub>	Tchobanoglous et al, 1993
Q <sub>Ch</sub>	11600 kJ/kg	Tchobanoglous et al, 1993
Q <sub>ev</sub>	2257000 J/kg	Incropera and Dewitt, 2002
P	750 kg/m <sup>3</sup>	Vesiland et al, 2002
ρ <sub>g</sub>	1 kg/m <sup>3</sup>	Incropera and Dewitt, 2002

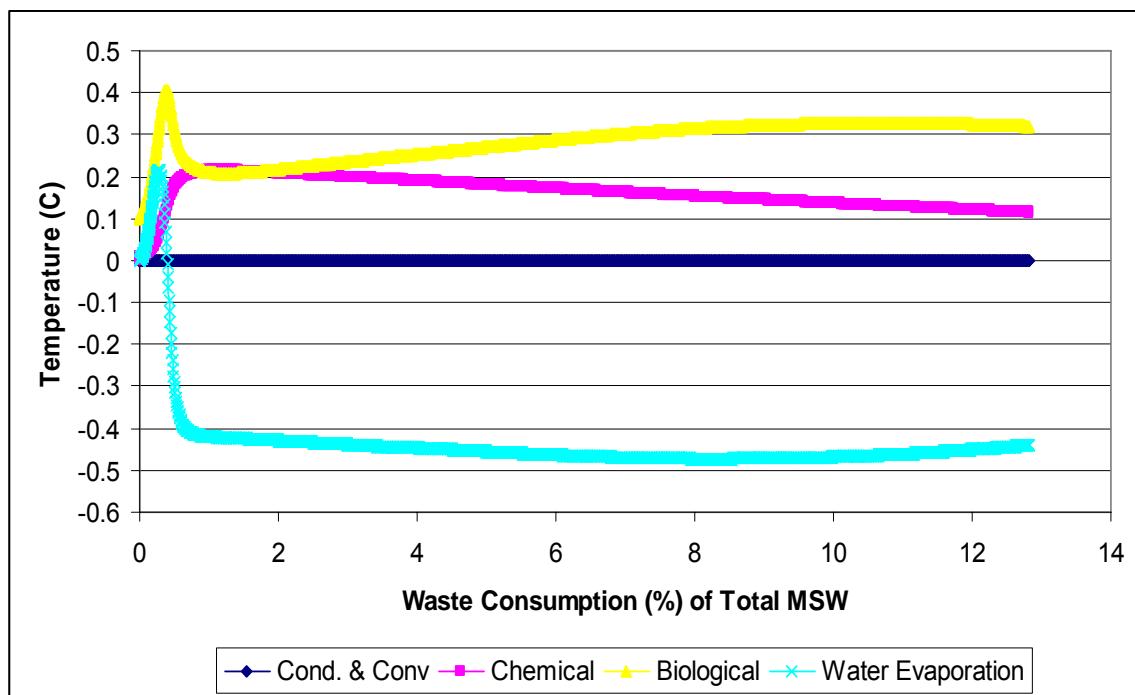


Figure 5.5: Profile of Energy Balance Equation Components in Aerobic Condition

## Simulation Scenarios

Four scenarios were selected as the most probable conditions for heat generation in landfills: anaerobic degradation, aerobic degradation, spontaneous combustion, and rapid reactive solid waste. Temperature increase among the scenarios occurs at different time scales, therefore, MSW consumption was used as the basis for comparison of the scenarios.

### ***Scenario 1: Anaerobic Degradation***

Operating a landfill under anaerobic conditions has been historically the most widespread practice. Heat generation under anaerobic conditions occurs at relatively low temperature (25-55°C) and is driven by microbial degradation of waste. Results from model simulation are

presented in Figure 5.6. The model predicts an increase in temperature from ambient temperature up to 42°C. Then, temperature declines as biodegradable MSW is consumed. For this simulation, initial moisture content is assumed to be 30% by weight dry basis and is sufficient to support degradation.

### ***Scenario 2: Aerobic Degradation***

Scenarios 2 and 3 correspond to the condition of operating an aerobic landfill or introducing air unintentionally by over drawing on the gas collection system. Scenario 2 represents the condition where heat generated is mainly due to microorganisms activities. Chemical oxidation occurs in this scenario, but it is negligible compared to the aerobic degradation.

Similar to anaerobic conditions, temperature increases rapidly at the beginning then stabilizes. In this simulation, temperature reaches 63°C which is higher than anaerobic conditions. Results from the model simulation are presented in Figure 5.6. Lethal temperature limit for microorganisms plays a significant role in the heat generation of the landfill. In this scenario, gas flow rate was assumed to be  $3.5 \times 10^{-5} \text{ m}^3/\text{s}$ , which is sufficient to control the temperature in a range that supports microbial activity. A higher flow rate would result in greater evaporation rates producing more heat loss and a decrease in the landfill temperature.

### ***Scenario 3: Spontaneous Combustion***

This scenario represents the heat generation from biological activities and chemical oxidation reactions leading to elevated temperatures in the landfill. The biological heat generation prevails from ambient room temperature to 65°C, while chemical oxidation dominates at temperatures

higher than 65°C. Simulations were conducted for two conditions, both of them aerobic, hot-spot and spontaneous combustion. Results from model simulation are presented in Figure 5.6.

Initially temperature increases rapidly due to the aerobic degradation of the solid waste. As temperature increases, chemical oxidation becomes more effective and heat generation increases. As in Scenario 2, water evaporation serves as a heat sink, however insufficient gas flow rate and, consequently, water evaporation in elevated landfill temperature. The hot-spot develops when heat generation and water evaporation balance result in temperature higher than 100°C. Gas flow rate is assumed to be  $7 \times 10^{-6}$  m<sup>3</sup>/s. Spontaneous combustion occurs in the simulation when the water evaporation rate is not adequate to balance the heat generated (See Figure 5.6). Gas flow rate is assumed to be  $3 \times 10^{-6}$  m<sup>3</sup>/s. The simulation was stopped when temperature reached 200°C as further increase in temperature caused the model to diverge and no solution could be attained. It is assumed that beyond this point combustion will continue, consuming all the combustible material.

Considering simulation results, gas flow rate is a major factor in heat dissipation because higher gas flow rates carry more water. Therefore, higher gas flow rate results in higher heat loss and lower temperatures in the landfill. Water evaporation appears to be the controlling factor in spontaneous combustion in landfills. However, as pointed out earlier, this simulation does not consider the effect of gas flow rate on oxygen supplies. Lower gas flow rate will also decrease the amount of oxygen which may limit heat generation.

#### **Scenario 4: Reactive Solid Waste**

Heat generation in MSW landfills may also result from exothermic reaction of by-product chemicals such as iron sulfide and pyrophoric compounds that release significant amounts of heat in the absence of oxygen such as the reaction between water and aluminum dross (EPA, 2008). Hence, water works as a heat sink through evaporation, but also is a key to heat generation. However, as water evaporates and is carried away by gas, less is available to react and consequently less heat is generated. Therefore, as the waste dries, reactions should stop. Unfortunately, quantitative information regarding heat generation and reaction kinetics is not available and it was not possible to simulate the scenario.

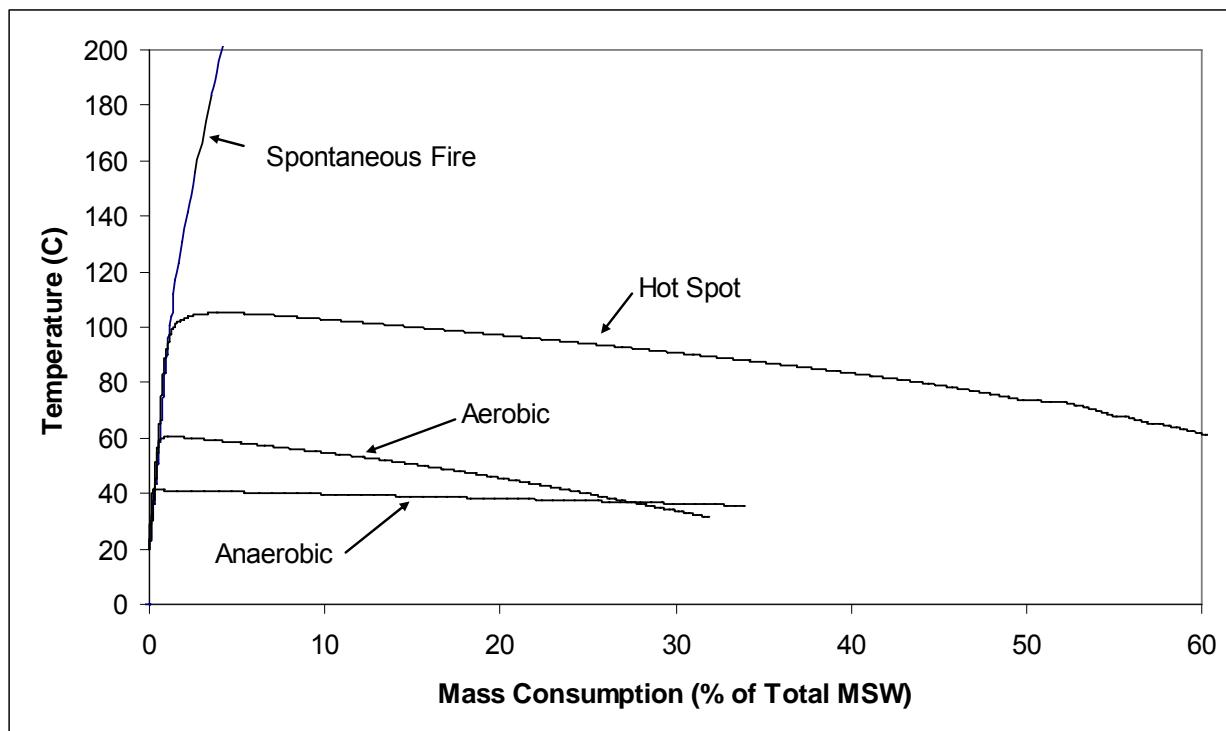


Figure 5.6: Temperature profiles of modeled landfill scenarios

## **Conclusions**

A model was created to simulate temperature rise in landfill for four different scenarios. Results indicated moisture evaporation as the major heat sink in the landfill. The model showed that gas flow has a cooling effect due to evaporation of water. However, increasing the flow rate may provide more oxygen to oxidize the solid waste, enabling chemical oxidation and concomitantly increasing heat generation. The addition of oxygen-free gas can reduce the landfill temperature through water evaporation without promoting oxidation. The model showed that the proper gas flow rate can control the temperature rise inside the landfill. The model also showed that temperature higher than the biological limit can be maintained in the landfill without initiating spontaneous fire. Elevated temperatures in the landfill may release products of incomplete combustion such as carbon monoxide without flammable combustion. The model was able to show that insufficient heat sinks leads to rapid increase in temperature, ignition, and combustion.

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## CHAPETR SIX CONCLUSIONS AND RECOMMENDATION

### **Conclusions**

Few studies have been conducted on spontaneous fires in landfills. To date little information has been presented regarding the thermal behavior of solid waste and measurements of spontaneous ignition of solid waste have not been made. In this study spontaneous combustion in municipal solid waste was investigated. The study enabled a better understanding of the self-heating process and spontaneous combustion in landfills. Effects of parameters critical to landfill operation on spontaneous combustion were determined.

A survey was distributed to landfill operators collecting information regarding spontaneous fires incidents at their landfills. Survey results raised new questions necessitating further study of subsurface fires incidents. Subsurface spontaneous fires were not restricted to any specific landfill geometry or type of waste (municipal, industrial, commercial, and C&D). Results showed that landfill fires occur in landfills that both do and do not recirculate leachate. Although new methods have been developed to detect subsurface fires, landfill operators depend primarily on visual observation of smoke or steam to detect the subsurface fires. Also, survey results indicated that excavating and covering with soil are the most widespread methods for extinguishing subsurface fires.

Methane has often been suspected to initiate spontaneous subsurface firs in the landfill. However, a combustible mixture of methane and oxygen requires very high temperature to ignite

(> 500°C). In this study it was shown that spontaneous fires are initiated by solid materials with lower ignition point. Laboratory tests were conducted evaluating the effect of moisture content, oxygen concentration and leachate on spontaneous ignition of solid waste. The crossing-point method was used to study the spontaneous combustion of solid waste and to determine the auto-ignition temperature (AIT) of the solid waste components and a synthesized solid waste. In addition, three characteristics temperature points were used to characterize spontaneous combustion of solid waste. These three points and the AIT allowed better understanding of self-heating and material behavior during slow heating. Correlations have been established between AIT, specific weight and energy content and between self-heating temperature and specific weight which indicate that compaction can help avoid spontaneous combustion in the landfill. Dense materials require higher energy to increase in temperature and they limit the accessibility of oxygen. Compaction was found to be of significant effect on thermal behavior of solid waste samples. In this study compaction was done by hand, mechanical or other compaction methods are suggested for better control of the samples density.

Based on the laboratory experiment, moisture can generally promote both biological and chemical self-heating. Increasing moisture content lowers the solid waste permeability and absorbs more energy as the liquid evaporates. Dissolved solids in leachate were found to promote self-heating and ignition more than distilled water. Test with varying oxygen concentrations suggested that heat generation occurs due to chemical oxidation even at oxygen concentration as low as 10% by volume. At 10% by volume oxygen, self-heating did not exhibit thermal runaway nor flammable combustion. At 0% by volume oxygen, self-heating occurred due to slow pyrolysis. An increase in temperature caused solid waste to char, creating a weak

structure. Also, it was concluded that heat generated from chemical oxidation plays a major role in spontaneous combustion.

A model was created to simulate temperature rise in landfill for four different scenarios. Results indicated moisture evaporation as the major heat sink in the landfill. The model showed that gas flow has a cooling effect due evaporation of water. However, increasing the flow rate may provide more oxygen to oxidize the solid waste, enabling chemical oxidation and concomitantly increasing heat generation. The addition of oxygen-free gas can reduce the landfill temperature through water evaporation without promoting oxidation. The model showed that the proper gas flow rate can control the temperature rise inside the landfill. The model also showed that temperature higher than the biological limit can be maintained in the landfill without initiating spontaneous fire. Elevated temperatures in the landfill may release products of incomplete combustion such as carbon monoxide without flammable combustion. The model was able to show that insufficient heat sinks leads to rapid increase in temperature, ignition, and combustion.

## **Recommendations**

This work provides a significant step towards full understanding of spontaneous combustion in landfills. However, questions remain and further study and investigation is needed. Testing plastic was not successful by the methodology proposed in this work due to the low melting temperature of plastic. A different approach for testing plastic is needed. Effect of solid waste components in each other was not investigated; testing mixture of 2 or 3 components might give

more information of solid waste behavior.

Oxygen plays a major role in the self-heating process. The model used in this study can be improved by including the effect of oxygen availability in the heat generation process by considering the role of gas flow rate in the model energy balance in supplying oxygen and considering oxygen depletion as biological consumptions occurs. Leachate contains a large number of constituents that affect the heat generation in solid waste in different ways. The collective influence of these constituents and their concentrations on heat generation in solid waste should be evaluated. An index parameter is recommended to represent the effect of leachate based on the constituent concentration and their impact on the heat generation.

This study did not contribute significantly to subsurface fires detection. Further study is recommended to determine better detection methods of subsurface fires to enable landfill operators to distinguish subsurface fires from hot spots. A pilot-scale study is suggested to evaluate the parameters controlling the spontaneous combustion. Pilot scale studies will provide important information on fires detection by monitoring gas and liquid discharges, among other tests. However, there are significant challenges in conducting such a study safely. Further the propagation of fire, once initiated should be studied to evaluate the effect on landfill structure and components and the timescale for fire incidents.

APPENDIX:  
SURVEY QUESTIONNAIRE



University of Central Florida

Civil & Environmental Engineering Department

Landfill Spontaneous Fires

Questionnaire



This survey is part of a study investigating the spontaneous underground fires or piles fires incidents in landfills. Therefore, this survey is directed only to the landfill cell that has experienced a spontaneous underground fire.

**Landfill cell information** (this information is for the cell in which the fire occurred):

1. What type of landfill cell do you own or operate?

- Above ground landfill
- Underground landfill
- Both

2. What type of landfill cell operation do you have?

- Conventional
- Bioreactor

3. Do you recirculate leachate?

- Yes
- No

4. Do you inject other liquids?

- Yes
- No

5. What type of waste does the landfill cell receive? (Check all that apply)

- Commercial
- Industrial
- Municipal
- Demolition

Construction

6. Is the waste pretreated prior to placing it in the cell (e.g. shredded, wetted, separated, baled, ...etc), if so, how?

.....  
.....  
.....

7. How old is the landfill cell that experienced the fire? .....years

8. How far is the landfill from developed areas? .....miles

9. What is the size of the cell that experienced the fire?

.....

10. How many times has the cell experienced a fire in the past (both surface and subsurface fires)?

.....

11. Were the fires spontaneous underground fires (underground fire that did NOT, for example, result from lightening striking well header)?

Yes

No

12. If yes, how many times have subsurface fires happened in that cell?

.....

13. How old was the cell when the first spontaneous subsurface fire happened?

.....year(s)

14. Is the cell lined?

Yes

No

15. if liner is used, what type of liner was it?

.....

16. How many other cells are at the landfill (operating and closed) ?

.....

17. Have you had fires at these other cells in the past?

Yes

No

18. Have you had spontaneous fires in storage piles (e.g. tires piles or green waste piles)?

Yes

No

19. If yes, what was the material stored in the pile?

.....  
.....  
.....

#### **Fire incidents information**

1. When spontaneous underground fires occurred, what sort of events happened prior to the fire detecting the fire?

- Rain
- Strong winds
- Dumping of hot loads
- Other:

.....  
.....

2. How was the spontaneous underground fire detected?

- Smoke
- Steam vents
- Cracks in the cell cap
- Sudden depression in the surface level
- High concentration of carbon monoxide in the landfill gas
- Reduction in the landfill gas production
- Other:

.....  
.....

3. What methods were used to extinguish the spontaneous fire?

- Excavation of smoldering material and spreading and compacting in an open area
- Pouring water in sinkholes
- Covering smoke vents with soil
- Injection of inert gas
- Other:

.....  
.....

4. What events accompanied the extinguishing of the spontaneous underground fire?

- Bursting of waste into flames
  - Collapse of the landfill structure
  - Haze formation
  - Smell
  - Other:
- .....  
.....

5. How long did it take to extinguish the fire? .....day(s)

6. Did anyone get injured from the fire?

- Yes
- No

7. Is there any observation that is not mentioned in this questionnaire?

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8. Will you please provide your contact information, incase we need clarification from you?

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