SANITARY LANDFILL

Suman Ghosh
Mission Geoscience, Inc., Irvine, California 92612, U.S.A.

Syed E. Hasan
Department of Geosciences, University of Missouri-Kansas City, Kansas City, Missouri 64110-2499, U.S.A.

Keywords: Sanitary landfill, leachate, landfill gas, bioreactor landfill, greenhouse gas, site selection.

Contents

Summary

Sanitary landfill represents one of the oldest and most common methods of municipal solid waste (MSW) disposal. Over the years, with the advancement of science and technology, design, operation, and maintenance of sanitary landfills have greatly improved resulting in facilities that are efficient, environmentally compatible, and free from many of the problems that created an image of a “dirty, smelly, and leaky” facility.

Indeed, modern landfills that are properly designed and comply with all regulations that go into site selection, design, construction, and operation of landfills, assure not only a clean and safe facility but a potential source of energy that helps in reduction of greenhouse gases that contribute to global warming. Once the waste is disposed of into

a sanitary landfill, its organic constituents undergo a complex series of physical, chemical and biological reactions, causing its conversion into simpler compounds. The rate of waste degradation depends on various factors, and generally takes several years for the process to complete.

The main by-products of reactions are landfill gases and leachate, generated at various stages of waste decomposition. Proper management of landfill gases and leachate is essential to prevent environmental pollution. Extensive landfill design criteria, including proper site selection, for construction of new landfills and expansion of existing landfills, have been developed to address various environmental and aesthetic concerns. If properly designed and managed, sanitary landfill is still the best economical solution for MSW disposal.

This paper discusses the salient features and general design principles of sanitary landfills.

1. Introduction

Waste generation can be traced as far back as the beginning of human civilization. The term 'waste' is defined as any material that is discarded, abandoned, or is not of any direct economical value to its owner and which bears an environmental liability. Waste can be broadly classified into solid, liquid, or gaseous wastes with many other intermediate categories (for example semi-solid, semi-liquid etc.). Of these, solid waste is one of the most critical one from waste management point of view, as without proper disposal it can cause air, land, and water pollution; odor, spread of different types of vector-borne diseases, and aesthetic deterioration of the environment.

Landfilling – defined as placing solid and semi-solid wastes on the ground, compacting and covering it with suitable materials to isolate it from the environment – is still one of the most common and favored methods for solid waste disposal. In recent years expansion of cities and growth of human population worldwide have resulted in a decrease in availability of land for waste disposal. In addition, years of uncontrolled and unplanned dumping of waste on land have caused severe groundwater, soil, and air pollution in different parts of the world.

Awareness of and necessity for effective solid waste management led to the modern day concept of sanitary landfill. Most of the developed and developing countries today use design criteria that take into account topography, site geology, and hydrogeology, along with engineering, economic, and legal requirements for the construction and operation of landfills.

In general, solid waste comprises non-liquid, non-soluble materials ranging from municipal garbage to industrial wastes that contain complex and hazardous substances (Shah, 2000). Solid waste includes household garbage, commercial waste, industrial waste, wastewater treatment plant sludge, sewage, agricultural refuse, construction and demolition (C & D) wastes, mining residues, etc. Municipal Solid Waste (MSW), which is a part of the total solid waste stream, includes commercial and residential wastes generated in municipal areas, either in solid or semi-solid form, excluding industrial hazardous wastes. In the United States in 2007, the total amount of MSW generated was 254 million tons (230.4 million metric tons; MMT), or 4.62 lb (2.1 kg) /person/day of which 137.2 million tons (124.5 MMT) or 54% was disposed of in landfills (U.S. EPA, 2008).

Landfill design includes protective measures against pollution of groundwater, surface water, fugitive dust, wind-blown litter, odor, fire hazard, bird menace, pests or rodents, greenhouse gas emissions, slope instability, and erosion (The Gazette of India, 2000). Solid wastes are disposed of in a landfill in thin layers, compacted to the smallest practical volume, and covered with suitable earth material each day to abate environmental pollution (Weiss, 1974). These measures minimize potential pollution problems and isolate the waste from exposure to the environment, making it "sanitary."

Sanitary landfills have also been loosely defined as disposal facilities that normally, but not necessarily, are located in areas serving populations of 5,000 or more and may accept all types of municipal solid wastes (Environmental Protection Division, Government of British Columbia, 1993).

The concept of sanitary landfilling was first introduced in the United Kingdom in 1912; in the United States sanitary landfilling became a common method of MSW disposal during the 1930s (Hasan, 1996). The Fresno Sanitary Landfill, located in Fresno, California, is the oldest sanitary landfill in the United States that started in 1937 and ceased its operation in 1987 (Historicfresno.org, 2008).

Based on the most recent data available with the United States Environmental Protection Agency (U.S EPA), municipal solid waste generation has grown steadily in the United States, from 88 million tons (79.83 MMT) in 1960 to over 254 million tons (230.4 MMT) in 2007 (U.S. EPA, 2008). During the 1960s and 1970s most of the MSW was disposed of as open dumps and a portion burnt to reduce its volume. Increasing concern for maintaining air and water quality gradually changed this age-old practice and led to disposal of waste in sanitary landfills.

According to the most recent data, the number of sanitary landfills in the United States has decreased steadily during the past decades, from 7,924 in 1988 to 1,754 in 2007 (U.S. EPA, 2008). As the number of landfills decreased, the size of landfills became larger, keeping the landfill capacity relatively constant. In 2007, the total MSW landfill capacity left in the United States was estimated to be 7,406 million tons (6,718.6 MMT), which was slightly higher than the remaining MSW landfilling capacity of 6,542 million tons (5,934.8 MMT) as was estimated in 1991 (Waste Business Journal, 2008).

Increasing interest in resource recovery, reuse, and recycling along with adoption of best management practices have led to considerable decrease in the bulk of MSW that ends up in landfills, which in turn has increased the number of years of available landfill capacity. Improved engineering design and sound environmental practice in landfill construction and maintenance have also increased the capacity and life of many existing landfills.

2. Biochemical Processes in Sanitary Landfill

Waste decomposition in sanitary landfill is a complex process achieved through sequential and sometimes simultaneous occurrence of a variety of chemical and biochemical reactions, resulting in degradation of waste materials. Organic fractions of MSW easily decompose leading to generation of landfill gases and liquids.

Initially, the biochemical reactions in a sanitary landfill take place under aerobic condition (where oxygen is the terminal electron acceptor), producing carbon dioxide (CO_2) as the principal gas. As most of the available oxygen (O_2) is depleted, decomposition reactions continue under partial aerobic to mostly anaerobic conditions, where the principal landfill gases generated are CO_2, methane (CH_4), trace amounts of ammonia (NH_3), and hydrogen sulfide (H_2S). The generalized biochemical reaction for the anaerobic decomposition of MSW can be expressed as (Tchobanoglous *et al.*, 1993):

$$+CO_2 + \text{other gases} \qquad (1)$$

Based on the generation of principal landfill gases and physico-chemcial conditions, five sequential phases can be identified over the lifetime of a sanitary landfill (Figure 1). Duration of individual phases, and nature and quantity of various landfill gases generated during each phase, are primarily dependent on the amount of biodegradable organic matter present in the waste, availability of moisture and nutrients necessary for biodegradation, and final landfill closure measures.

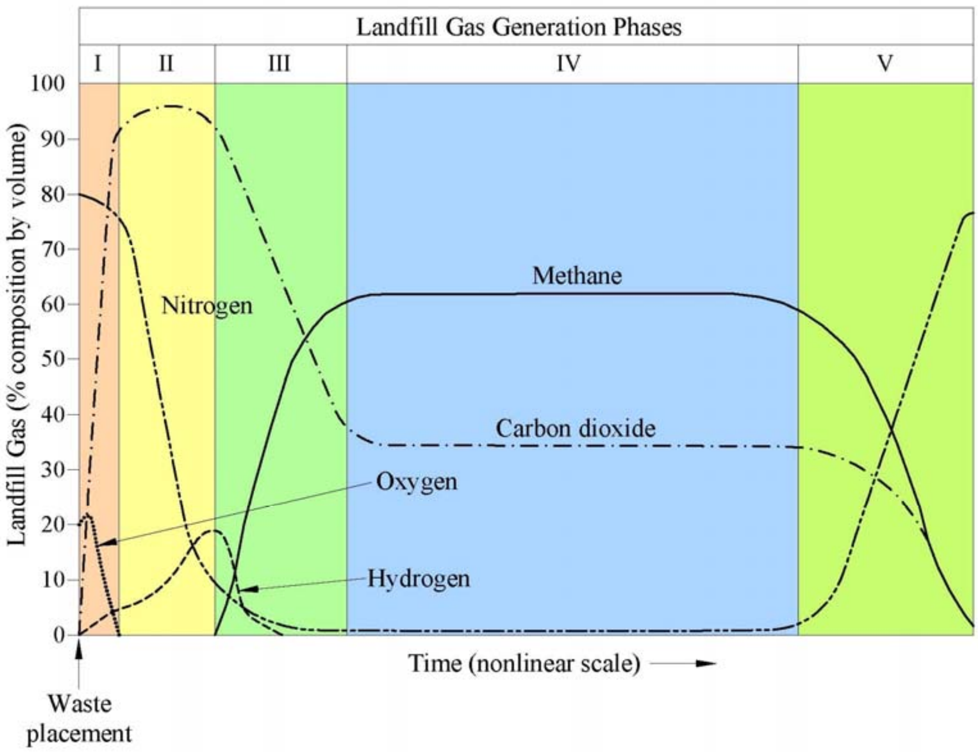

Figure 1. Schematic representation of landfill gas generation phases.
[Adapted from: U.S. EPA, 2004 and other sources.]

Phase I – Initial Adjustment: This is the initial phase in the life cycle of a sanitary landfill during which the organic constituents easily biodegrade: organic compounds in the MSW undergo microbial decomposition mostly under aerobic conditions as soon as they are placed in the landfill and soon thereafter. Typical duration of this phase is few hours to about a week from the time of waste emplacement (Tchobanoglous *et al.*, 1993).

The air trapped within the landfill supplies O_2 promoting aerobic processes. Microorganisms – the principal agents in biodegradation – mainly come from the soil used for daily cover. Sometimes wastewater treatment plant sludge and recirculated leachate also act as sources of microbial population necessary for bio-decomposition of the waste. Primary gases generated in Phase I are N_2 and O_2 that occur in the same proportion as in the atmosphere.

Phase II – Transition Phase: This is partly aerobic and partly anaerobic phase during which transition from aerobic to anaerobic condition occurs within the landfill. Oxygen, already consumed and depleted during Phase I, leads to mostly anaerobic condition. In the absence of O_2, nitrate and sulfate become the terminal electron acceptors generating nitrogen and hydrogen sulfide respectively.

The transition from aerobic to anaerobic conditions can be monitored by measuring the oxidation/reduction potential of the waste (Tchobanoglous *et al.*, 1993). Any leachate formed during the transition phase is generally acidic in nature due to the generation of organic acids and elevated concentrations of CO_2 within the landfill. pH during this phase usually ranges from 6 to 7 (Pohland and Kim, 1999) and typical duration of this phase is approximately 1 to 6 months.

Phase III – Acid Phase: In this phase, the microbial activities increases significantly leading to generation of considerable amounts of organic acids and minor quantities of hydrogen (H_2) gas. This is a three-step process of which the first step involves hydrolysis where lipids, polysaccharides, proteins, nucleic acid, and other higher molecular-mass compounds undergo enzyme-mediated transformation and change into compounds that are used by microorganisms as a source of energy.

The second step, called acidogenesis, involves biochemical conversion of higher molecular-mass compounds, resulting from the first step reaction, into lower molecular-mass intermediate compounds, mainly acetic acid (CH_3COOH), with small concentrations of fulvic and other complex organic acids (Tchobanoglous *et al.*, 1993). The third step results in conversion of the intermediate compounds, through microbial activities, into simpler products, mainly CO_2 and CH_4 that attain its peak in Phase IV. The microorganisms, referred to as acidogens or acid formers, are dominated by facultative and obligate anaerobic bacteria.

Any leachate that might form in Phase III is acidic, with pH of 5 or less (due to the presence of organic acids and higher concentrations of CO_2 in the landfill). Because of the lower pH many inorganic constituents, including heavy metals, are dissolved in the leachate that makes it highly toxic. Typical duration of this phase is approximately 3 months to 3 years.

Phase IV – Methane Fermentation Phase: This phase is unique for its methane generation. A specific group of strict anaerobes, called methanogens, convert CH_3COOH and H_2, formed in Phase III, to CH_4 and CO_2. Although acid production still continues, the rate of acid formation is substantially reduced that causes the pH of the leachate to increase toward neutral values (between 6.8 and 8) during Phase IV (Tchobanoglous *et al.*, 1993). Continued rise of pH ultimately causes some inorganic constituents to precipitate out of the leachate. Typical duration of this phase is approximately 8 to 40 years, and the principle gases are CH_4 and CO_2.

Phase V – Maturation Phase: This is the last phase in the life cycle of a sanitary landfill. Once the easily biodegradable organic materials are depleted (as discussed earlier), microorganisms start decomposing other difficult to biodegrade materials during Phase V. However, the rate and extent of biodegradation depend on availability of moisture. CH_4 and CO_2 are the principal landfill gases generated during this phase; and small amounts of O_2 and N_2 may also be found depending on the landfill closure measures (Tchobanoglous *et al.*, 1993).

The rate of landfill gas generation decreases sharply from the previous phases as the amount of available biodegradable organic matter is greatly depleted during the maturation phase. The leachate generated at this phase often contains humic and fulvic acids that are recalcitrant compounds and are very difficult to biodegrade. Typical duration of this phase is approximately 1 to 40 years.

3. Landfill By-Products: Leachate and Gas

As discussed before, the two main by-products generated during the life of a landfill are leachate and landfill gases. Landfill leachate may be defined as a toxic, mineralized liquid, generated during the waste decomposition process. Depending upon the nature of waste and design of the landfill, the composition and amount of leachate and gas generated vary to a great extent. This section describes the nature of leachate and landfill gases and the associated management system that is needed for proper functioning of a sanitary landfill.

3.1. Landfill Leachate

Chemically bound water which is present in many MSW constituents, along with water from external sources, such as rainfall, snowmelt, groundwater, springs, surface water bodies, etc., entering through the solid waste results in removal of many biological and chemical materials in solution (leachate), causing it to acquire a very high dissolved and suspended solid content, both organic and inorganic. Based on the nature of solid waste and age of the landfill, composition of the leachate also varies.

The biodegradability of leachate depends on the amount of biological materials present in the leachate, which varies during the life of a landfill. The BOD_5/COD ratio provides a good measure of biodegradability of the leachate that typically ranges between 0.05 and 0.2 in mature landfills. Higher BOD_5/COD ratio indicates presence of easily biodegradable materials in the leachate while low BOD_5/COD ratio indicates presence of difficult-to-biodegrade materials.

Leachate is generally collected at the bottom of the landfill; in unlined landfills, leachate usually migrates through the underground strata and may travel down to the groundwater table. Some lateral migration of the leachate is also possible depending on the subsurface geology.

The migrating leachate can dissolve soluble chemicals, many with toxic constituents that may result in groundwater pollution. Hence proper leachate management procedures should be developed and incorporated into the design of landfills. In the U.S.A., double liners, and leachate and gas management systems are required by law for all landfills built after 1994.

One of the key components of leachate management system is the use of landfill liner to control/restrict the movement of leachate offsite. Different types of liner systems are used depending on the characteristic of the leachate, subsurface geology and other design objectives.

Clay is the most commonly used liner material, but geosynthetic membrane liners are also widely used in sanitary landfills. As part of the leachate management system a grading plan is developed which includes installation of drainage channels and pipelines for leachate collection and transport.

Leachate collection, removal, holding, and treatment facilities are also part of the leachate management system. Leachate collected from landfills is generally placed in holding tanks for 1-3 days, but is eventually disposed off through leachate recycling, evaporation, underground injection, physical-chemical, or biological treatment, and/or discharged into municipal sewer system after treatment.

The leachate disposal method depends on the nature of the leachate, the quantity of leachate generated, subsurface geology, local government policies, etc.

Design of the landfill liner system and layout of leachate collection pipes hold the key to successful operation of a leachate management system. The liners are generally placed at a minimum of 2% slope and pipes are laid at 1% slope (minimum) to facilitate the flow of leachate through the collection system (Tchobanoglous *et al.*, 1993). This prevents the accumulation of leachate in the low lying areas of the landfill.

Leachate collection pipes are generally placed in a trench or on the liner and are buried in a bed of gravel to protect it from crushing due to overburden pressure. Subsurface barriers are also sometimes used in association with natural geologic materials to prevent lateral leachate migration.

Barriers are designed and constructed to prevent build up of any hydraulic head against the structure. This is accomplished by using a minimum of 2 feet (0.61 m) of clay or a minimum of 40 mils of synthetic materials (Tchobanoglous *et al.*, 1993).

-
-
-

Bibliography

Bioreactor.org (2009). *What is a bioreactor landfill?* Available at: http://www.bioreactor.org/info.html. Accessed November 17, 2009. [This presents SWANA's definition of bioreactor landfill.]

Environmental Protection Division, Ministry of Water, Land and Air Protection, Government of British Columbia (1993). *Landfill Criteria For Municipal Solid Waste*. Available at: http://wlapwww.gov.bc.ca/epd/epdpa/mpp/lcmsw.html#RTFToC6. Accessed September 15, 2004. [This presents information on the landfill construction, design and site selection criteria (including sanitary landfills) in British Columbia.]

European Commission (1996). *Strategy paper for reducing methane emissions*. Available at: http://aei.pitt.edu/3919/01/000141_1.pdf. Accessed December 18, 2009. [This paper addresses problems and concerns related to atmospheric methane emissions and potential measures for reducing emissions.]

Hasan S.E. (1996). *Geology and Hazardous Waste Management*. Upper Saddle River: Prentice Hall. [This book provides readers a thorough understanding of the principles of management of hazardous waste and emphasizes the critical relationship between geology and hazardous waste management.]

Historicfresno.org (2008). *Fresno Sanitary Landfill (1937)*. Available at: http://historicfresno.org/nrhp/landfill.htm. Accessed March 31, 2008. [This presents the historical records of Fresno Sanitary Landfill.]

IPPC (1996). *Climate Change 1995: 'The Science of Climate Change', Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change.*

Pohland, F., and Kim, J. (1999). *In situ Anaerobic Treatment of Landfills for Optimum Stabilization and Biogas Production*. Water Science and Technology, 40(8), 203-210. [This article provides information on landfill gas generation phases.]

Shah K.L. (2000). *Basics of Solid and Hazardous Waste Management Technology*. Upper Saddle River: Prentice Hall. [This book presents an introduction to solid and hazardous waste and the issues associated with them.]

Tchobanoglous G., Theisen H. and Vigil S. (1993). *Integrated Solid Waste Management: Engineering Principles and Management Issues*. Boston: Irwin McGraw-Hill. [This book provides the engineering and scientific aspects of integrated solid waste management in conjunction with the principles of waste management to its audience.]

The Gazette of India (2000). *Ministry of Environment and Forests Notification*. Available at: http://www.envfor.nic.in/legis/hsm/mswmhr.html. Accessed October 10, 2004. [This presents the municipal solid waste disposal rules of Government of India.]

U.S. Environmental Protection Agency (1995). *Decision Maker's Guide to Solid Waste Management*, Volume II. EPA530-R-95-023. [This document presents information on design criteria for sanitary landfill.]

U.S. Environmental Protection Agency (2004). *Monitoring Approaches for Landfill Bioreactors*. EPA/600/R-04/301. [This document presents information on different landfill waste decomposition and gas generation phases.]

U.S. Environmental Protection Agency (2008). *Municipal Solid Waste in the United States: 2007 Facts* *and Figures*. EPA 530-R-08-010, 177 p. Available at: http://www.epa.gov/epawaste/nonhaz/municipal/pubs/msw07-rpt.pdf . Accessed November 20, 2009. [This document presents facts and figures on municipal solid waste disposal in the United States for the year 2007.]

U.S. Environmental Protection Agency (2009a). Landfill Methane Outreach Program (LMOP). Available at: http://www.epa.gov/lmop/. Accessed November 1, 2009. [This presents information on LMOP.]

U.S. Environmental Protection Agency (2009b). *Bioreactors*. Available at: http://www.epa.gov/epawaste/nonhaz/municipal/landfill/bioreactors.htm. Accessed November 20, 2009. [This presents an overview of bioreactor landfills.]

United States Government (2009). *Code of Federal Regulations,* Title 40, Part 258, §258.10. Available at: http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&rgn=div5&view=text&node=40:24.0.1.4.38&idno=40#40:24.0.1.4.38.2.23.1. Accessed Dec. 29, 2009. [Comprehensive sets of rules and regulations dealing with *Protection of Environmen*t codified in 40 CFR 260 to 265 and 40 CFR 266 to 299.]

Waste Business Journal (2008). *Remaining capacity of MSW Landfills*. Personal communication received on July 30, 2008. [Provides most recent MSW landfill information.]

Weiss S. (1974). *Sanitary Landfill Technology*. London: Noyes Data Corporation. [This book presents valuable information on sanitary landfill design, construction and operation.]

Biographical Sketches

Suman Ghosh is an environmental scientist with interdisciplinary studies in geology, hydrogeology, chemistry, and environmental microbiology. He holds a doctorate in environmental science (applied geosciences) from the University of Missouri at Kansas City. Over the last eight years Dr. Ghosh has worked as a hydrogeologist/environmental consultant in the United States for both public and private sector clients, including the U.S. Army Corps of Engineers, U.S. Army, U.S. Air Force, Texas Dept. of Transportation, Alcoa, and Methode Electronics to name a few. Presently Dr. Ghosh is working as a senior project hydrogeologist at Mission Geoscience, Inc. in Irvine, California, where he is managing several large soil and groundwater investigation and remediation projects for the company.

Over the past several years Dr. Ghosh has worked extensively on various hazardous waste site investigation projects, including his active participation in a USEPA TRIAD RI/FS implementation. In the recent years, Dr. Ghosh has served as an expert in the fields of indoor-vapor intrusion, human health risk assessment, and groundwater remediation, utilizing enhanced natural attenuation.

Syed E. Hasan received his Ph.D. in *Engineering and Environmental Geology* from Purdue University in 1978 and joined the faculty of the University of Missouri at Kansas City in 1979 where he is currently serving as a Professor of Geology and Director of the Center for Applied Environmental Research (CAER), and the Graduate Certificate in Waste Management program.

Dr. Hasan authored a college textbook titled *Geology and Hazardous Waste Management* (Prentice Hall, 1996) for which the Association of Environmental and Engineering Geologists presented the *Holdredge Award* (1998). In June 2000 he received the *Educator's Environmental Excellence Award* from the U.S. Environmental Protection Agency for being the outstanding environmental educator in Missouri. In April 2005, the Department of Earth and Atmospheric Sciences, Purdue University, honored him with its *Outstanding Alumnus Award*. In October, 2009 the Geological Society of America's Engineering Geology Division honored him with its *Meritorious Service Award* for sustained contribution to the profession.

Dr. Hasan has presented lectures on waste management, environmental issues, and medical geology at Budapest, Hungary (1993), Kuwait (2001, 2003, 2006, 2009), Florence, Italy (2004), Cairo and Assiut, Egypt (2003, 2006), Shahrjah, U.A.E. (2005), Germany (2007), and India (2005, 2007, 2009). Dr. Hasan is a Registered Geologist in Missouri, U.S.A; Fellow of the Geological Society of America, Life Fellow of the Geological Society of India, and a member of several professional organizations. He is listed in the *American Men and Women of Sciences, Who's Who in Science and Engineering; International Man of the Year*, *Top 100 Scientists, Leading Educators of the World,* and the *International Bibliographical Centre,* *Cambridge, U.K.*

He was the chair of the Geological Society of America’s Engineering Geology Division (2007); and is currently (2009) serving as chair-elect of its Geology and Health Division, and on the editorial board of *Environmental & Engineering Geosciences*.