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Environmental Impacts of Solid Waste Landfilling

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Inevitable consequences of the practice of solid waste disposal in landfills are gas and leachate generation due primarily to microbial decomposition, climatic conditions, refuse characteristics and landfilling operations. The migration of gas and leachate away from the landfill boundaries and their release into the surrounding environment present serious environmental concerns at both existing and new facilities. Besides potential health hazards, these concerns include, and are not limited to, fires and explosions, vegetation damage, unpleasant odors, landfill settlement, ground water pollution, air pollution and global warming. This paper presents an overview of gas and leachate formation mechanisms in landfills and their adverse environmental impacts, and describes control methods to eliminate or minimize these impacts.

Keywords: landfill, solid waste disposal, biodegradation, gas and leachate generation, environmental impacts, control methods.

1. Introduction

Solid waste disposal in landfills remains the most economic form of disposal in the vast majority of cases (Thompson and Zandi, 1975; Rushbrook, 1983; Carra and Cossu, 1990). Therefore, landfills will continue to be the most attractive disposal route for solid waste. Indeed, depending on location, up to 95% of solid waste generated world-wide is currently disposed of in landfills (Bingemer and Crutzen, 1987; Cossu, 1989; Nozhevnikova *et al*., 1992; Gendebien *et al*., 1992). Alternatives to landfilling are considered as *volume reduction* processes because they produce waste fractions (e.g. ashes and slag from combustion processes that represent the second leading method of waste disposal) which ultimately must be landfilled (Emberton and Parker, 1987). Resorting to landfills is not limited to the disposal of municipal solid waste, but it includes most other industrial wastes. For instance, nearly 80% of hazardous wastes generated in the U.S. is dumped in landfills (Eichenberger *et al*., 1978).

Solid waste composition varies substantially with socio-economic conditions, location,

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TABLE 1. Typical solid waste composition

Waste category	Range Percent Dry Weight European Community	Range Percent Dry Weight United States	Typical Percent Dry Weight United States
Paper/cardboard	20–42	28–50	40
Food waste	20–50	6–18	9
Yard waste	12–18	5–20	18·5
Plastics	3–8	4–10	7
Glass	4–12	4–12	8
Metals	3–13	3–13	9·5
Wood/rubber/leather/textiles	2–14	1–12	5
Inerts/inorganics	1–20	0–6	3

From: Bonomo and Higginson, 1988; Tchobanoglous *et al.*, 1993; and US EPA, 1994.

TABLE 2. Solid waste chemical composition

Chemical Constituent	Range Percent Dry Weight	Average Percent Dry Weight
Cellulose, sugar, starch	52–64·5	58
Hemicellulose	11·9	11·9
Lignin	5·4–15·2	11·2
Lipids	5·7	5·7
Protein	2·6–4·2	3·4

From Pfeffer and Khan, 1976; Pfeffer, 1976; and Barlaz and Ham, 1993.

season, waste collection and disposal methods, sampling and sorting procedures, and many other factors (Bonomo and Higginson, 1988; Senior, 1990; Tchobanoglous *et al.*, 1993). Table 1 illustrates the wide range of values reported for waste categories typically encountered in solid waste. Despite the variability in its composition, total organic content (particularly cellulosic material), constitutes the highest percentage of solid waste (Table 2).

Most organic materials are biodegredable and can be broken down into simpler compounds by aerobic and anaerobic microorganisms, leading to the formation of gas and leachate. The following sections provide an overview of the mechanisms of gas and leachate formation in landfills, their environmental impacts, and appropriate control methods to eliminate or minimize these impacts.

2. Landfill Gas Formation Mechanisms

At the time of waste deposition in a landfill, oxygen is present in the void space, giving rise to aerobic decomposition during which biodegradable organic materials react quickly with oxygen to form carbon dioxide, water, and other by-products (e.g. bacterial cells). Carbon dioxide is produced in approximate molar equivalents to the oxygen consumed. Oxygen depletion within the landfill marks the onset of the anaerobic decompositon phase. Although a landfill ecosystem undergoes an initial short aerobic decomposition phase, the subsequent anaerobic phase is the dominant phase in its age and the more important one from the perspective of gas formation.

Much of what is known or assumed concerning anaerobic processes in landfills has primarily come from work with anaerobic digesters. Microbial populations in both environments appear to be similar however, the major difference is that the substrates may vary in their relative content of fat, protein, and carbohydrates, and conversely to landfills, the environment in anaerobic digesters is well controlled and often under optimal conditions.

Investigators have recognized several major steps to describe the anaerobic decomposition phase during which organic materials are converted to methane and carbon dioxide (Alexander, 1971; Zehnder, 1978; Wolfe, 1979; McCarty 1981; Zehnder *et al.*, 1982; Mosey, 1983; Archer and Robertson, 1986; Balba, 1987). These steps are highly inter-dependent and include hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Figure 1).

Generally, the breakdown of organic matter in anaerobic ecosystems proceeds sequentially from the complex to the simple starting with the hydrolysis of complex particulate matter to simpler polymers like proteins, carbohydrates and lipids which are further hydrolyzed to yield biomonomers like amino acids, sugars, and high molecular fatty acids. Amino acids and sugars are converted into either intermediate by-products (e.g. propionic, butyric and other volatile acids) or directly fermented to acetic acid. High molecular fatty acids are oxidized to intermediate by-products and hydrogen. Methane and carbon dioxide generation occurs primarily through acetate

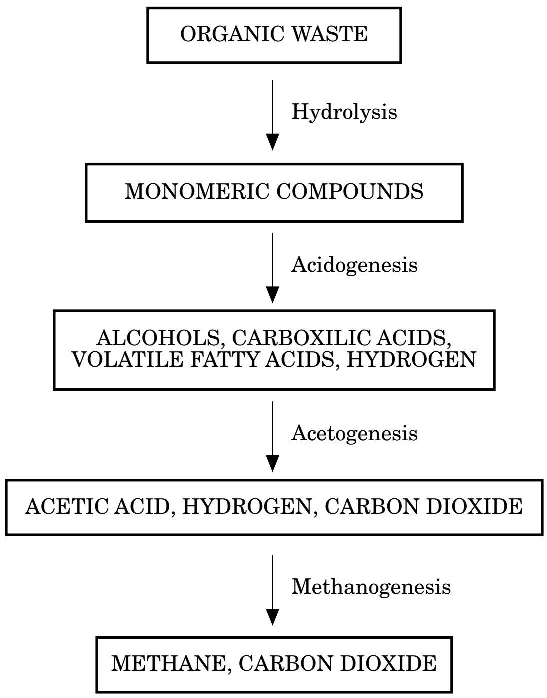

Figure 1. Major degradative steps during the anaerobic decomposition phase.

TABLE 3. Landfill gas composition

Component	Concentration Range Percent Dry Volume Basis
Methane	40–70
Carbon Dioxide	30–60
Carbon Monoxide	0–3
Nitrogen	3–5
Oxygen	0–3
Hydrogen	0–5
Hydrogen Sulfide	0–2
Trace Compounds	0–1

From: Robinson, 1986; Zimmerman and Issacson, 1988; and McBean *et al.*, 1995.

TABLE 4. Trace compounds in landfill gas

Category of Trace Constituents	Concentration Range mg/m^3
Alcohols	2–2500
Organosulphur compounds	3–240
Halogenated hydrocarbons	1–2900
Aromatic hydrocarbons	30–1900
Aldehydes	0–200
Ketones	0–50
Hydrocarbons:	
Alkanes	20–4500
Alkenes	6–1100
Cycloalkanes	1–1000
Cycloalanes	8–600
Esters	0–1300
Ethers	0–250

Lytwynyshyn *et al.*, 1982; Young and Parker, 1983; Young and Heasman, 1985; Rettenberg, 1994; Rettenberg, 1987; and Senior, 1990.

cleavage. Methane is also produced through carbon dioxide reduction with hydrogen. In a landfill environment, methane generation from the latter route is often limited by the lack of hydrogen which is consumed by sulfate reducers (Kasali, 1986).

Qualitatively, landfill gas is highly dependent on the decomposition stage within the landfill (Rovers and Farquhar, 1973; Rees, 1980; Pohland *et al.*, 1983; Barlaz *et al.*, 1989c). Under a stabilized methanogenic condition which is the stage of interest from a beneficial recovery perspective, methane and carbon dioxide are by far the two principal components of landfill gas and form more than 90% of the total gas generated. Nitrogen and oxygen are normally present in small quantities primarily as a result of air entrapment during waste deposition, atmospheric air diffusion through the landfill cover especially in the near surface layers, or air intrusion from negative landfill pressure when landfill gas is extracted. Table 3 summarizes the composition of a typical landfill gas. Hydrocarbons and trace compounds, which are present at a very low percentage, may be constituted of numerous chemicals as depicted in Table 4. As well as their potential adverse health effects and environmental pollution, trace compounds even at low levels could cause toxicity on microbial populations, and hence may inhibit gas formation and stabilization processes within a landfill.

Quantitatively, the gas yield which is defined as the total amount of gas produced by a unit weight of municipal solid waste over the landfill's gas generation time span, is of interest when controlling gas or attempting to recover it for beneficial purposes. Theoretical and experimental studies have attempted to estimate or measure the gas yield that is available in solid waste. Comprehensive reviews of this work have been conducted by several investigators (Ham *et al.*, 1979; EMCON, 1983; Halvadakis *et al.*, 1983; Pohland and Harper, 1986; Bogner, 1988; Ham and Barlaz, 1989; El-Fadel, 1991; Gendebien *et al.*, 1992; McBean *et al.*, 1995).

Theoretical estimates are based on two approaches: a *stoichiometric* approach that assumes an overall reaction for methanogenesis in which the reactant is the waste component and the products include methane and carbon dioxide or a *biodegradibility* approach that assumes a different biodegradation rate or half life value for different refuse components, or considers the biodegradation rate for each component in terms of volatile acids content and uses a common gas yield factor for all biodegradable volatile solids. The resulting yields from both approaches are at best rough estimates of the potential gas yield and should only be used in determining complete process conversion or in defining maximum attainable yields. The estimates over-simplify the complex process of refuse decomposition and do not account for numerous factors, including the extent of aerobic and anaerobic decomposition, nutrient limitations, biological inhibition, physio-chemical interactions and requirements for bacterial cell synthesis.

Experimentally, gas yields have been measured in anaerobic digestion studies (*digesters*), laboratory landfill-simulator studies (*lysimeters*), and field-scale studies (*test-cells*). Similar to theoretical estimates, the application of results obtained from experimental studies to a full scale landfill remains difficult, because they simulate only average landfill conditions and do not account for variations brought about by climatic and operational events. Gas yield from full scale landfills would be the best indicator. However, such data is very limited, if not non-existent, and is difficult to acquire given the complexity of biochemical interactions within a landfill, the lack of uniform and reliable data collection protocols, the inherent uncertainty of gas collection methods employed at various sites, and the maturation stage at which a landfill might be during a monitoring period (Pohland and Harper, 1986).

Table 5 present ranges of typical gas yield values from solid waste based on theoretical and experimental studies. Theoretical approaches generally result in higher gas yield estimates because they assume a biological ecosystem in which all waste constiuents or a well defined fraction of the waste will be directly converted to methane and carbon dioxide. Experimentally, *digesters* represent an optimized and well controlled environment in which gas generation is enhanced resulting in higher gas yields than lysimeters or field scale test cells. In *lysimeters*, the development of a stable methanogenic gas generation phase may never be accomplished because of less than optimum conditions (DeWalle *et al.*, 1978; Shafer *et al.*, 1981; Walsh *et al.*, 1982; Jones *et al.*, 1984). As such, lysimeter measurements exhibit greater variability. *Test-cells* are by far the most representative of landfill conditions because they are usually constructed within the landfill, subjected to identical climatic conditions and filled with the same waste material using similar operational procedures. They are often used to evaluate the effects of different management practices on landfill stabilization and methane yields

TABLE 5. Gas yield from municipal solid waste

Source	Gas Yield (l/kg) Dry Refuse	Methane Yield (l/kg) Dry Refuse
Theoretical: Stoichiometric Approach		
Anderson and Callinan, 1970	410	240
Alpern, 1973	420	210
Boyle, 1976	450	230
Ham, 1979	120–310	
Stearns and Wright, 1981		266
Theoretical: Biodegradability Approach		
Dair and Schwegler, 1974	190	90
Pfeffer, 1974	250	120
Pacey, 1976	120	60
Golueke, 1977	350	170
Experimental: Anaerobic Digesters		
Klein, 1972	240	130
Pfeffer, 1974	90–130	50–220
Hitte, 1976	210	120
Gossett *et al.*, 1982	290–390	200–280
Rees and Viney, 1982	0·5–57	
Emberton, 1986	0·1–174	
Barlaz *et al.*, 1989b		77–107
Haddad, 1990	12·1–82·8	21·2–223·8
Chukwu, 1991	54·4–191·6	43·5–95·8
Experimental: Lysimeters		
Merz and Stone, 1964	13	
Merz and Stone, 1968	4	
Ramaswami, 1970	1–180	1–70
Rovers and Farquhar, 1973	6	1
Augenstein *et al.*, 1976	250	130
DeWalle *et al.*, 1978	0·001–0·018	0·001
Pohland, 1980	7	4
Buivid, 1980; Buivid *et al.*, 1981	1–230	1–140
Shafer *et al.*, 1981	0·018	0·0018
Walsh *et al.*, 1982	0·003–0·018	
Jones *et al.*, 1984	17·8–20·1	0·038–0·096
Barlaz *et al.*, 1987		47–97
Ehrig, 1991	78–113	128–230
Experimental: Field Scale Test Cells		
Pacey and Dietz, 1986; Pacey, 1989	68–163	38·1–92·5
Croft, 1991	9·2–14·4	3·0–6·3

1 l/kg = 0·016 ft^3/lb

(refuse pretreatment and compaction; cover material and surface vegetation; irrigation and leachate recirculation; nutrient addition, bacterial seeding, etc.).

The gas generation rates, that are the controlling factors in assessing the feasibility of exploiting a landfill site, are often estimated on the basis of gas yield from experimental studies by averaging the yield over the duration of the study. Because of the different conditions under which these studies were conducted (waste composition, moisture content and application rates, pH, buffer, nutrients, temperature, etc.), data from field

TABLE 6. Gas generation rate from municipal solid waste

Source	Average Gas Generation Rate (l/kg/yr) Dry Refuse
Experimental: Anaerobic Digesters or Lysimeters	
Ramaswami, 1970	57–104
Rovers and Farquhar, 1973	7·25
Augenstein *et al.*, 1976	136–440
Chian *et al.*, 1977	0·09–6·45
DeWalle *et al.*, 1978	0·1–13
Pohland, 1980	2–32
Buivid, 1980	25–488
Walsh *et al.*, 1982	0·18
Klink and Ham, 1982	260
Jenkins and Pettus, 1985	43
Emberton, 1986	78–86
Barlaz *et al.*, 1987	24–200
Haddad, 1990	9–188
Chukwuk, 1991	340
Experimental: Field Scale Test Cells	
Pacey and Dietz, 1986; Pacey, 1989	15·6–37·5
Croft, 1991	13–19
Landfills	
EMCON, 1980a, 1983; US EPA, 1979	
Field Pump Testing	2·8–7·5
Gas control systems	4·9–5·7
Gas recovery systems	1–14

1 l/kg = 0·016 ft^3/lb

pumping tests or gas control systems provide more reasonable estimates (Table 6). While experimental studies resulted in gas generation rates on the order of 0 to 488 l/kg/yr, estimates from measurements at full scale landfills fall within a narrower range of 1 to 14 l/kg/yr.

In an actual landfill, whether the theoretical or experimental yield is ultimately produced will depend upon many variables influencing gas generation in anaerobic systems including waste characteristics, moisture content, temperature, pH, the availability of nutrients and microbes, and the presence of inhibitors. Figure 2 depicts these variables with landfill operational practices by which they may be affected or controlled.

The influence of these variables, the enhancement of gas yield and stabilization processes in landfills have been the focus of numerous studies in the past two decades. Comprehensive reviews of data from these studies have been presented in detail by many investigators (EMCON, 1980b, 1983; Halvadakis, 1983; Pohland and Harper, 1986; Pacey, 1986; Senior and Balba, 1987; Senior, 1990, Barlaz *et al.*, 1990; Gardner and Probert, 1993). Table 7 describes the general influence of these variables and represents an overall assessment of the consensus amongst reviewers based on the reported literature. It is a qualitative and sometimes a speculative assessment because experiments have not always been conducted in a systematic way where the influence of one single variable is independently evaluated. The observed effects are often the result of varying more than one variable at a time, which makes it difficult to qualitatively separate individual effects due to the strong interactions between these variables. The

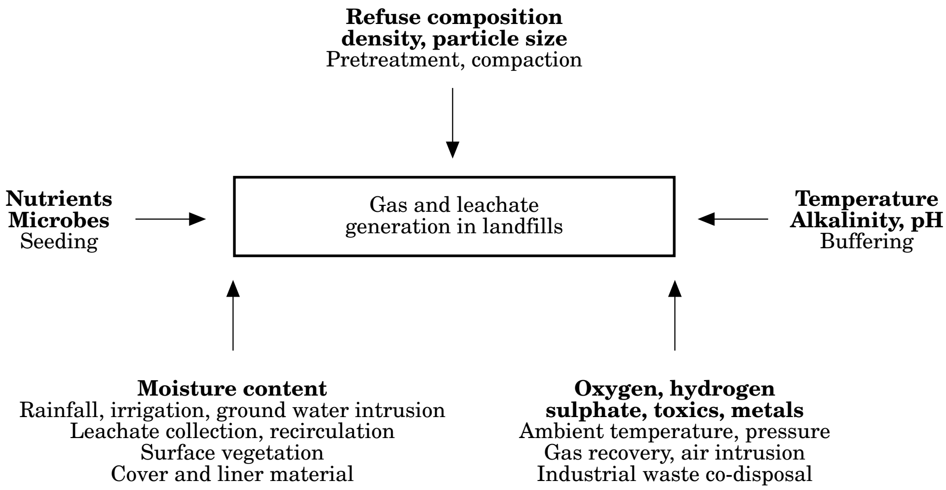

Figure 2. Factors influencing gas and leachate generation in landfills.

TABLE 7. Effect of variables influencing gas generation in landfills

Variable	Gas Enhancement Potential			Gas Inhibition Potential		
	Low	Medium	High	Low	Medium	High
Composition		+		–		
Density	+					
Particle size	+					
Temperature		+			–	
pH		+		–		
Nutrients	+			–		
Microbes	+			–		
Moisture			+			
Oxygen						–
Hydrogen	+			–		
Sulfate				–		
Toxics					–	
Metals				–		

variability in solid waste composition has also often resulted in contradictory results between studies or even between reactors within the same study, which makes extrapolations from experimental reactors to full scale field conditions inherently uncertain. Therefore, careful evaluation of these variables must be conducted in the field before adopting any specific enhancement technique, particularly that the control of gas generation by manipulation of a single site variable may result in operational constraints and may mediate changes in other variables (Mouton, 1984).

3. Leachate Formation Mechanisms

Leachate formation is the result of the removal of soluble compounds by the non-uniform and intermittent percolation of water through the refuse mass. Soluble compounds are

TABLE 8. Chemical composition of leachate from municipal solid waste

Parameter	Concentration Range mg/l	Parameter	Concentration Range mg/l
Alkalinity (as $CaCO_3$)	0–20 850	Nitrogen (Ammonia)	0–1250
Aluminium	0·5–85·0	Nitrogen (Nitrate)	0–9·8
Antimony	0–3·19	Nitrogen (Nitrite)	0–1·46
Arsenic	0–70·2	Nitrogen (Organic)	0–1000
Barium	0–12·5	Nitrogen (Kjeldahl)	3320
Berylium	0–0·36	Nickel	0–7·5
BOD_5*	0–1 95 000	Phenol	0·17–6·6
Boron	0·413	Phosphorus (Total)	0–234
Cadmium	0–1·16	Phosphate	0·01–154
Calcium	5–4080	pH	1·5–9·5
Chloride	11 375	Potassium	0·16–3370
Chromium	0–22·5	Selenium	0–1·85
COD†	0–89 520	Silver	0–1·96
Conductivity (μmho/cm)	480–72 500	Sodium	0–8000
Copper	0–9·9	Thallium	0–0·32
Cyanide	0–6	Tin	0–016
Fluoride	0·1–1·3	TDS‡	584–55 000
Hardness (as $CaCO_3$)	0·1–225 000	TSS§	140 900
Iron	0–42 000	TOC‖	335 000
Lead	0–14·2	TVA¶ (as Acetic Acid)	0–19 000
Magnesium	115 600	Turbidity	40–500
Manganese	0·05–1400	Sulfate	0–1850
Mercury	0–3	Zinc	0–1000

* Biochemical Oxygen Demand; † Chemical Oxygen Demand; ‡ Total Dissolved Solids; § Total Suspended Units; ‖Total Organic Carbon; ¶Total Volatile Acids.
From: Halvadakis, 1993; Pohland and Harper, 1986; Robinson, 1986; Ehrig, 1988; Bagchi, 1989; and Harris and Gaspar, 1989.

generally encountered in the refuse at emplacement or are formed in chemical and biological processes. The sources of percolating water are primarily the precipitation, irrigation, and runoff which cause infiltration through the landfill cover; ground water intrusion, and to a lesser extent, the initial refuse moisture content. Refuse decomposition due to microbial activity may also contribute to leachate formation but in smaller amounts. The quantity of leachate generated is site-specific and a function of water availability and weather conditions as well as the characteristics of the refuse, the landfill surface, and underlying soil.

The quality of landfill leachate is highly dependent upon the stage of fermentation in the landfill, waste composition, operational procedures, and co-disposal of industrial wastes (Hoeks and Harmsen, 1980; Parker and Williams, 1981; Harmen, 1983; Pohland *et al.*, 1983). Many chemicals (e.g. metals, aliphatics, acyclics, terpenes, and aromatics) have been detected in landfill leachate from domestic, commercial, industrial, and co-disposal sites. Table 8 shows the range of composition for a variety of leachates from landfills where reportedly, only municipal solid waste were buried. Although it is difficult to generalize concerning the particular chemical concentration that a leachate will contain, the trend of continually decreasing concentration is a generally observed phenomenon (Rees, 1980; Pohland *et al.*, 1983; Halvadakis *et al.*, 1983; Pohland and Harper, 1986; Ehrig, 1988; Barlaz, 1988; Mukesh, 1992).

3.1. LEACHATE EFFECT ON LANDFILL GAS FORMATION

Laboratory and field studies have shown that leachate organic content is microbially degradable under either aerobic or anaerobic conditions (Boyle and Ham, 1974; Uloth and Mavinic, 1977; Cameron and Koch, 1980a,b; Beard and McCarty, 1983; Pohland and Harper, 1986). However, in light of their highly variable nature, leachates might become toxic to methanogenesis in landfills especially where domestic waste is co-disposed with industrial wastes. For instance, leachate with pH values as low as 1·5 and as high as 9·5 have been reported in the literature. Although a rare occurrence, such pH values could cause a complete inhibition to the growth of methanogens which usually grow best at pH values ranging from 6 to 8 (Clarck and Speece, 1971; Zehnder *et al.*, 1982; Gujer and Zehnder, 1983).

Another perspective on leachate effect on gas formation that has been documented in the literature is leachate recirculation as a landfill management option (Pohland and Kang, 1974; Pohland *et al.*, 1979; Pohland, 1980). Recirculation has been reported to accelerate stabilization in lysimeter studies as well as at field scale test cells (Leckie *et al.*, 1979; Tittlebaum, 1982). Fast stabilization may enhance methanogenesis and gas formation (Klink and Ham, 1982; Buivid, 1980). In some cases however, inhibition of methanogenesis for unknown reasons was attributed to leachate recirculation (Barlaz *et al.*, 1989a; O'Connor *et al.*, 1990).

4. Environmental Impacts

Historically, landfills were initiated largely as a result of a need to protect the environment and society from adverse impacts of alternative methods of refuse disposal such as open-air burning, open-pit dumping, and ocean dumping (Senior, 1990). Although landfills eliminated some impacts of old practices, new ones arose, primarily due to gas and leachate formation. Besides potential health hazards, these concerns include fires and explosions, vegetation damage, unpleasant odors, landfill settlement, ground water pollution, air pollution and global warming.

4.1. FIRE AND EXPLOSION HAZARDS

Although landfill gas rich in methane provides an energy recovery opportunity, it has often been considered to be a liability because of its flammability, its ability to form explosive mixtures with air, and its tendency to migrate away from the landfill boundaries by diffusion and advection. Diffusion is the physical process that causes a gas to seek a uniform concentration throughout the landfill volume, hence the gas moves from areas of higher to areas of lower concentration. Advection results from pressure gradients where gas moves from zones of higher to zones of lower pressure. Diffusion and advection rates depend primarily on the physical properties and generation rates of the landfill gas, refuse permeability, internal landfill temperature, moisture content, surrounding soil formation and changes in barometric pressure.

Landfill gas moves along routes that will allow it to escape from the landfill either by venting through the cover or by moving through the sides to the surrounding soil. The migrating gas finds its way into buildings and underground facilities erected on, or near to, a landfill site where it forms gas pockets and creates potential explosive hazards. Depending on the soil characteristics, the gas may travel long distances away from the landfill prior to being discovered. Numerous incidents of fires and explosions due to lateral gas migration away from landfills have been reported in the literature (MacFarlane, 1970; Environ, 1975; McOmber and Moore, 1981; Parker, 1981; Shafer *et al.*, 1984; Raybould and Anderson, 1987).

Fire and explosion hazards are not limited to incidents away from the landfill. On-site fires are common and many occur in the subsurface due to air entrainment into the landfill and the formation of a mixture of methane and oxygen that can sustain a fire (Stearns and Peyotan, 1984a). Air entrainment occurs primarily as a result of excessive withdrawal rates from gas recovery or migration control systems. In addition, surface cracks and temperature gradients can create a chimney effect and entrain air into the landfill. Techniques employed to control a subsurface fire include excavation, smothering (by eliminating the air supply into the landfill thus depriving it from oxygen), and injection of inert gas or water (Stearns and Peyotan, 1984b).

4.2. VEGETATION DAMAGE

At closure, many landfill sites are converted to parks, golf courses, agricultural fields, and in some cases, commercial developments. Vegetation damage at or nearby to such sites is well documented in the literature (Flower *et al.*, 1977, 1981; Leone *et al.*, 1977; Leone and Flower, 1982; Gilman, 1980; Gilman *et al.*, 1981, 1982, 1985; Arthur *et al.*, 1985). The damage occurs primarily due to oxygen deficiency in the root zone resulting from a direct displacement of oxygen by landfill gas. In the absence of a gas control measure, landfill gas can migrate upward due to concentration and pressure gradients, and escape into the atmosphere by venting through the landfill cover. During this process, oxygen is displaced and plant roots are exposed to high concentrations of methane and carbon dioxide, the two major constituents of landfill gas. The lack of oxygen causes the death of plants of asphyxia.

Although direct exposure to methane may not affect the growth of plants, methane oxidation near the surface by methane-consuming bacteria (methanotrophs) is another factor that contributes to oxygen deficiency. The significance of this microbial activity in shallow soils has been reported by many investigators (Adamse *et al.*, 1972; Hoeks, 1972, 1983; Mancinelli *et al.*, 1981; Harriss *et al.*, 1982; Keller *et al.*, 1983; Conrad, 1984; Mancinelli and McKay, 1985; Striegl and Ishii, 1989; Bogner *et al.*, 1990; Jones, 1992). Oxygen is consumed in accordance with:

$$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O + \text{Heat}$$

Heat release during methane oxidation increases the soil temperature creating a potential for plant asphyxia (Hewitt and McRae, 1985). Carbon dioxide generation from methane oxidation and landfill gas can be harmful to plant growth particularly at high concentrations (30 to 45%). Other commonly reported factors that may affect growth of plants at landfill sites include the presence of trace toxic compounds in landfill gas and cover soil characteristics such as thickness, composition, compaction and moisture.

4.3. UNPLEASANT ODORS

Odors are mainly the result of the presence of small concentrations of odorous constituents (esters, hydrogen sulfide, organosulphurs, alkylbenzenes, limonene and other hydrocarbons) in landfill gas emitted into the atmosphere (Young and Parker, 1983, 1984). The odorous nature of landfill gas may vary widely from relatively sweet to bitter and acrid depending on the concentration of the odorous constituents within the gas. These concentrations will vary with waste composition and age, decomposition stage and the rate of gas generation, and the nature of microbial populations within the waste, amongst other factors. Although many odorous trace compounds may be toxic, they have historically been perceived more as an environmental nuisance than as a direct health hazard (Young and Parker, 1984; Young and Heasman, 1985). The extent to which odors spread away from the landfill boundaries depends primarily on weather conditions (wind, temperature, pressure, humidity).

4.4. LANDFILL SETTLEMENT

Development of completed landfill sites is invariably hindered by significant settlements caused primarily by refuse decomposition which increases the void ratio and weakens the structural strength of the refuse within a landfill leading to a substantial loss of volume and settlement. Other causes of landfill settlement include refuse dissolution into leachate; incomplete waste compaction; movement of smaller particles into larger voids created by biological and physico-chemical changes, and subsurface fires (raveling); consolidation or mechanical compression due to the refuse thickness and own weight, or the load of construction material and structures erected on the landfill (Sowers, 1968; Yen and Scanlon, 1975; Murphy and Gilbert, 1985; Edgers *et al.*, 1992).

The rate and magnitude of landfill settlement depends primarily on the refuse composition, operational practices and factors affecting biodegradation of landfill waste, particularly moisture (James, 1977; Edil *et al.*, 1990; Wall and Zeiss, 1995). Estimates of the total settlement in a landfill range from 25 to 50% of the original thickness (Stearns, 1987). Operational and load-related settlements typically constitute 5 to 30% of total settlement and occur during landfill operations or shortly after closure (Sowers, 1973; Edil *et al.*, 1990). Long-term settlements due primarily to refuse decomposition can theoretically reach 40% of the original thickness (Cheyney, 1983; Emberton and Parker, 1987) and occur gradually for several years after closure at a continually decreasing rate (Dodt *et al.*, 1987; Coduto and Huitric, 1990) depending on stabilization processes within the landfill. On average, settlement of about 15% of total landfill thickness is expected due to waste decomposition (Rao *et al.*, 1977; Tang *et al.*, 1994).

Landfills often exhibit great variations in waste composition resulting in a non-uniform settlement pattern. This creates differential settlements which can have a devastating effect on the integrity of any structure erected on the landfill. Structural failures of buildings, surface cracks in the final cover, damage to the surface water drainage system, piping of leachate and gas collection systems, and underground utilities are commonly attributed to differential settlements (Sowers, 1968; Stearns, 1987; Held, 1990). As well as variations in waste composition, changes in the manner in which the waste is placed or compacted, localized raveling, vertical loads, and subsurface fires can also contribute to differential settlements. Operational and maintenance practices (sorting, pretreatment, uniform compaction, etc.) can minimize problems associated with both total and differential settlements.

4.5. GROUND WATER POLLUTION

Leachate occurrence is by far the most significant threat to ground water. Once it reaches the bottom of the landfill or an impermeable layer within the landfill, leachate either travels laterally to a point where it discharges to the ground's surface as a seep, or it will move through the base of the landfill and into the subsurface formations. Depending upon the nature of these formations and in the absence of a leachate collection system, leachate has reportedly been associated with the contamination of aquifers underlying landfills which resulted in extensive investigations for the past four decades (Zanoni, 1972; Walls, 1975; Dunlap *et al.*, 1976; Kelly, 1976; MacFarlane *et al.*, 1983; Cheremissinoff *et al.*, 1984; Reinhard *et al.*, 1984; Ostendorf *et al.*, 1984; Mackay *et al.*, 1985; Albaiges *et al.*, 1986; Mann and Schmadeke, 1986). In fact, it is speculated that in the U.S., contamination by municipal landfills, to which every household contributes more than a gallon of hazardous wastes per year (Lee *et al.*, 1986), could become a bigger problem than contamination associated with the sole disposal of hazardous wastes in landfills (Senior, 1990). Currently, it is estimated that over 25% of the Superfund sites listed on the National Priority List are solid waste landfills (Arigala *et al.*, 1995).

As well as leachate, landfill gas contains a high concentration of carbon dioxide which reportedly presents a significant ground water pollution potential because of its high solubility (Kaszynski *et al.*, 1981). Furthermore, the emission of trace toxic gases within landfill gas has been established to cause a serious threat to air and ground water resources. Several examples are documented in the literature on the presence of vinyl chloride and other volatile hydrocarbons in ground water at distances away from municipal landfills (Stephens *et al.*, 1986). As a result, transport mechanisms of trace gas in unsaturated porous media have recently been the subject of many investigations (Mason and Malinuskus, 1983; Jury *et al.*, 1983; Abriola and Pinder, 1985; Baehr, 1987; Silka, 1988; Sleep and Sykes, 1989; Falta *et al.*, 1989). It is suggested that trace toxic gases emitted with landfill gas travel in the unsaturated zone and come into contact with ground water resulting in aqueous–gaseous phase partitioning at the interface and as such, polluting ground water resources.

4.6. AIR POLLUTION

Although methane and carbon dioxide are the two major components of the gas emitted from landfills, there is evidence that this gas contains numerous other constituents in trace amounts significant enough to cause environmental and health concerns (Lytwynyshyn *et al.*, 1982; Young and Parker, 1983; Karimi, 1983; Gianti *et al.*, 1984; Harkov *et al.*, 1985; Todd and Propper, 1985; Young and Heasman, 1985; Wood and Porter, 1986; Rettenberg, 1984, 1987). Potential emissions of Volatile Organic Compounds (VOCs) from landfills can range from 4×10^{-4} to 1×10^{-3} kg/m^2/day (US EPA, 1989).

The presence of these chemicals in landfill gas can be attributed to regular household, co-disposal of light industrial wastes, or illegal dumping. Microbial investigations indicate that biodegradation by-products within the landfill can also contribute to the formation of many of these chemicals (Vogel and McCarty, 1985; Hallen *et al.*, 1986; Molton *et al.*, 1987). The primary concerns of trace gas emissions are air pollution and potential health hazards. The emission of VOCs is believed to have the potential to increase cancer risks in local communities and contribute to ambient ozone formation (Shen *et al.*, 1990). Trace gases may also affect methane generation by inhibiting the growth of methanogens, and may cause corrosion of gas recovery equipments (Dent *et al.*, 1986).

4.7. GLOBAL WARMING

Atmospheric gas emission rates through a landfill cover have been measured by several investigators. During dry soil conditions at a semi-arid landfill site, Bogner *et al.* (1989) indicated that methane and carbon dioxide fluxes may be as high as 630 and 950 kg/m^2/yr, respectively. Using flux box measurements, Lytwynyshyn *et al.* (1982) and Kunz and Lu (1979, 1980), estimated that methane diffusion flux through landfill covers ranged between 390 and 1200 kg/m^2/yr. These measurements are likely to underestimate actual emission rates because of aerobic oxidation of methane near the surface by methanotrophs. Although emission rates from controlled experiments may not be representative of actual emissions from landfills, they clearly demonstrate the propensity of gas release into the atmosphere.

Emissions of methane and carbon dioxide from landfill surfaces contribute significantly to global warming or the greenhouse effect. Methane has received recent attention as a contributor to global warming because on a molecular basis, it has a relative effect 20 to 25 times greater than carbon dioxide (Lagerkvist, 1987; Blake and Rowland, 1988; Augenstein, 1990), it is more effective at trapping infrared radiation (Bingemer and Crutzen, 1987) and tends to persist longer in the atmosphere owing to other species (i.e. carbon monoxide) with a greater affinity for hydroxyl ions, the oxidizing agent for methane (Dickenson and Cicerone, 1986; Gardner *et al.*, 1993).

Recent increases of methane concentrations in the atmosphere have lead to extensive characterization studies of global methane sources and sinks. Atmospheric methane concentrations were reported to increase at an average rate of about 1 to 2% per year (Khalid and Rasmussen, 1983; Kerr, 1984; Marland and Rotty, 1985; Matthews and Fung, 1987; Mooney *et al.*, 1987; Thornoloe and Peers, 1990). It is estimated that methane contributes about 18% towards total global warming (Church and Shepherd, 1989). This contribution represents 500 million tons per year approximately of which 40 to 75 million tons are attributed to emissions from landfills (Sheppard *et al.*, 1982; Senior and Balba, 1987; Bingemer and Crutzen, 1987; and Pearce, 1989). Due to continuing trends in population increase and urbanization, solid waste landfills are becoming a significant contributor to atmospheric methane, unless recovery control systems are implemented.

5. Landfill gas and leachate control

Landfill gas control measures are essential in order to eliminate or minimize its associated adverse environmental impacts. In most cases the installation of a gas recovery, collection and treatment system will assist in preventing gas migration away from the landfill boundaries or gas emissions through the landfill surface. Indeed many of the early gas recovery projects were developed as a consequence of, or as an adjunct to, existing gas migration control schemes. When landfill gas is recovered appropriately its methane content represents an energy reservoir of great potential. It is estimated that annual gas generation potential in the US alone exceeds 6 billion m^3 (Dawson, 1981; Marchant, 1981). The energy represented by this gas could meet 1% of the total energy needs or 5% of the natural gas utilization in the U.S. (Lytwynyshyn *et al.*, 1982). Reported estimates of worldwide annual gas generation potential vary widely, 30 to 430 billion m^3 (Bingemer and Crutzen, 1987; Lagerkvist, 1987; Dessanti and Peter, 1984; Sheppard *et al.*, 1982). The upper range is questionable, particularly when compared with methane yield data from actual landfills with a recovery system.

Leachate treatment system

Gas treatment/recovery system

Landfill cover
Top slope (2–6% typ.)
Vegetative soil layer (12″–24″ typ.)
Geotextile membranes
Clay layer (18″–24″ typ.)
Permeability<1 10^{-8} cm/s

SIDE LINER

Leachate collection and removal system
Perimeter drainage channel
Drainage layer (1′ typ.)
Pipes (4″–6″ typ.)

Gas control system
Active pumping
Passive venting
Perimeter barriers

SIDE LINER

Leachate collection and removal system
Drainage layer (1′ typ.)
Pipes (4″–6″ typ.)

Bottom liner
Geotextile membranes
Clay layer (3′ typ.)
Permeability<1 10^{-8} cm/s

Figure 3. Typical components of a controlled landfill disposal facility.

The economic feasibility of landfill gas recovery, processing, and utilization have indeed been demonstrated and reported by many investigators at sites under different climatic conditions (Boyle, 1976; Lockman, 1979; Kaszynski *et al.*, 1981; EMCON, 1983; Mouton, 1984; Wiqwist, 1986; Gendebien *et al.*, 1992). New landfills can be designed to prevent landfill gas accumulation even if no productive use of the gas is planned. Landfill gas control systems have been well documented in engineering practice (Weiss, 1974; Stone, 1978a,b; Goleuke, 1980; Shen, 1981; Stearns and Peyotan, 1981; EMCON, 1983; Pacey, 1984; Ghassemi *et al.*, 1986; Walsh *et al.*, 1988; Shen *et al.*, 1990). In addition to gas recovery and active gas pumping, control measures include: (1) the installation of impermeable barriers before site operations to secure the perimeter of the landfill (cement walls, clay trenches, impervious liner materials such as plastics, rubber, asphalt, polyvinyl chloride, high density polyethylene, etc.); (2) passive venting consisting of a trench installed beyond the landfill boundary and backfilled with coarse material (e.g. gravel) to create a zone of high permeability which would be preferentially used by the gas; (3) a hybrid system consisting of any combination of impermeable barriers and an active or passive system (Alzaydi, 1980). Injection of lime slurry and fly ash has also been reported to control methane formation and stabilize landfills by inhibiting methanogenesis and stopping landfill gas generation (Kinman *et al.*, 1988).

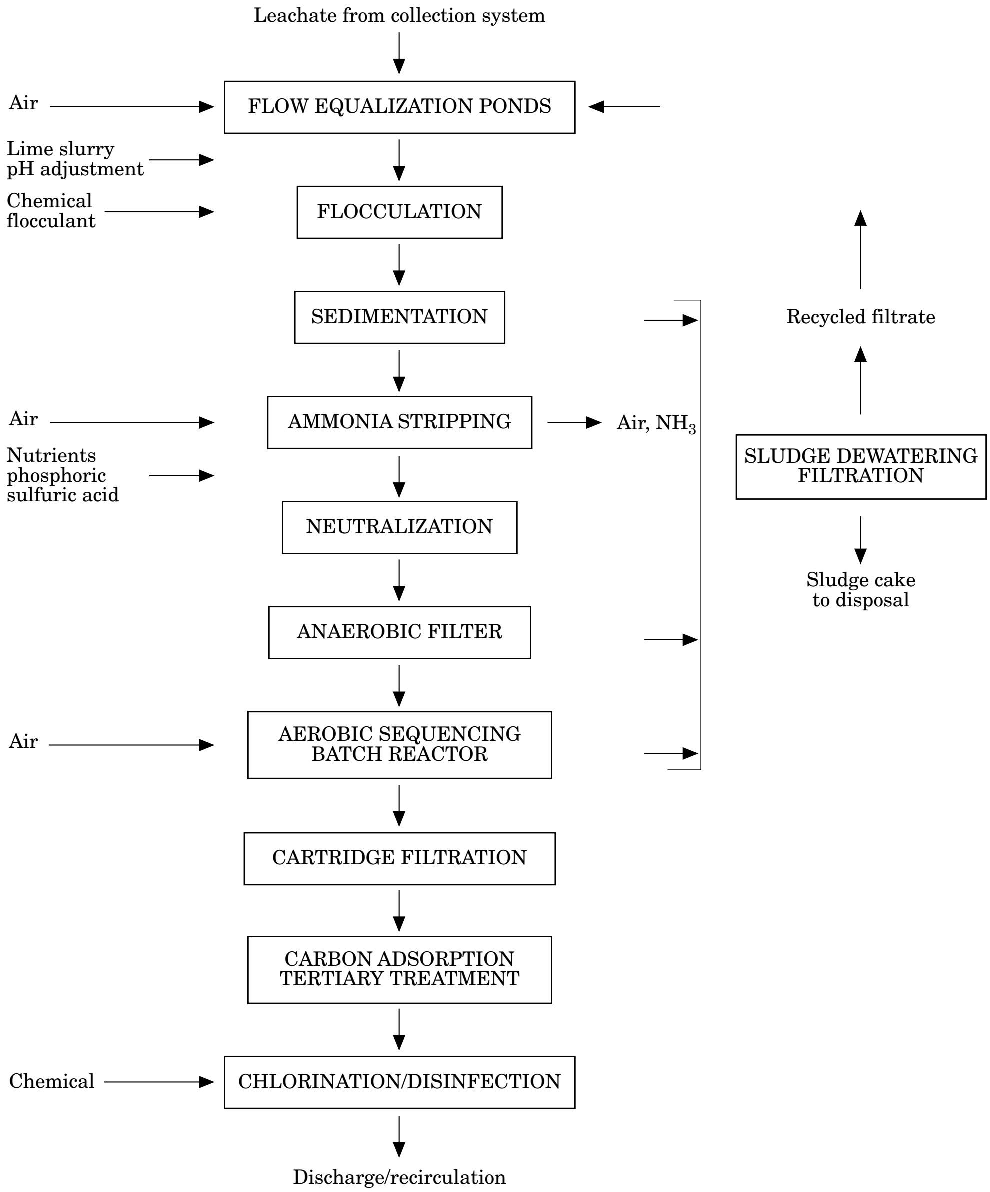

Figure 4. Process flow diagram for a hypothetical leachate treatment system.

Landfill leachate control measures include volume and composition control, treatment and disposal. Hydraulic barriers (e.g. extraction and relief wells, gradient control wells and trenches and collection systems are commonly used to control leachate problems, Hermann and Lowe, 1987; Harris and Gaspar, 1989). Typically, landfill boundaries (bottom, sides, and top) are covered by a clay or synthetic liner to minimize leachate formation through infiltration or ground water intrusion. The landfill cover is designed with a sloping surface to enhance surface runoff, which is collected via drainage channels constructed at the surrounding edge of the landfill. Water from precipitation or irrigation that may infiltrate past the landfill cover can be collected via a leachate collection and removal system located under the cover and/or above the bottom liner. In cases where fast stabilization by moisture addition and leachate recirculation is practised, the collection system under the landfill cover is not desired. At the bottom of the landfill, the system prevents the buildup of hydrostatic pressure which could lead to extensive breaching of the bottom liner resulting in leachate migration and pollution of underlying aquifers. The collected leachate is generally treated on-site and disposed of to a nearby sewer system or by recirculation. Figure 3 illustrates desired components of a well controlled landfill disposal facility.

Leachate composition can be controlled to a limited extent by close monitoring and sorting of landfill waste. However, decomposition byproducts dissolved in infiltrating water will result in a leachate with elevated concentrations of numerous hazardous chemicals. Leachate treatment is often necessary to reduce these concentrations to levels that meet regulatory requirements. Most biological, physical and chemical processes used for the treatment of industrial wastewater have been tested for treatment of landfill leachates (Pohland and Harper, 1986). The selection of a particular treatment process will depend on the quality and strength of the leachate. Figure 4 shows a hypothetical leachate treatment system utilizing important unit operations as suggested by Harris and Gaspar (1989).

6. Summary and conclusions

Gas and leachate generation are inevitable consequences of the practice of waste disposal in landfills. Microbial decomposition, climatic conditions, refuse characteristics and landfilling operations are amongst the many factors contributing the gas and leachate generation at landfill sites. The migration of gas and leachate away from the landfill boundaries and their release into the surrounding environment present serious environmental concerns at both existing and new facilities including potential health hazards, fires and explosions, damage to vegetation, unpleasant odors, landfill settlement, ground water pollution, air pollution and global warming.

An overview of gas and leachate formation mechanisms in landfills and their associated adverse environmental impacts was presented and a description of control methods to eliminate or minimize these impacts was provided. In most cases the installation of a gas recovery, collection and treatment system will assist in preventing gas migration away from the landfill boundaries or gas emissions through the landfill surface. Hydraulic barriers (e.g. extraction and relief wells, gradient control wells and trenches) and collection systems are commonly used to control leachate problems.

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