CHAPTER 1
Introduction

1.1. Purpose and Scope. This EM establishes criteria and guidance for landfill off-gas collection and treatment systems.

1.2. Applicability. This EM applies to HQUSACE elements, major subordinate commands (MSC), districts, and field operating activities (FOA) with responsibilities for landfill off-gas collection and treatment systems.

1.3. References. Appendix A contains a list of references used in this EM.

1.4. Background. This EM provides information about the design of systems to monitor, collect, transport, and treat off-gas from municipal, industrial and hazardous waste landfills. The EM describes various landfill gas (LFG) emission control techniques and presents design procedures relative to each. The following topics are discussed in this EM:

- Reasons for LFG control.
- Theory of LFG emissions.
- LFG and condensate characteristics.
- Estimation of LFG production.
- LFG collection and treatment design considerations.
- Operation and maintenance requirements.
- Regulatory requirements.

1.4.1. *Reasons for Landfill Gas Control.* The following is a list of common reasons for controlling the gas produced by a landfill:

- Prevent air pollution and comply with regulatory air emission criteria.
- Reduce hazards due to off-site migration.
- Prevent damage to the landfill cover slope stability.
- Odor control.
- Energy recovery.
- Prevent vegetation distress.

1.4.2. *Gas Generation Mechanisms*. LFG emissions are governed by gas-generation mechanisms and gas-transport mechanisms. The following paragraphs describe these mechanisms and the major factors influencing gas generation and transport. The three primary causes of LFG generation are volatilization, biological decomposition, and chemical reactions.

1.4.2.1. *Volatilization.* Volatilization is due to the change of chemical phase equilibrium that exists within the landfill. Organic compounds in the landfill volatilize until the equilibrium vapor concentration is reached. This process is accelerated when biological activity increases the temperature of the waste mass. The rate at which compounds volatilize depends on their physical and chemical properties. Some of these properties are discussed in the following paragraphs.

1.4.2.2. *Vapor Pressure.* Vapor pressure quantifies the tendency of a pure liquid compound to partition to the vapor phase. Liquid molecules that possess sufficient kinetic energy are projected out of the main body of a liquid at its free surface and pass into vapor. The pressure exerted by this vapor is known as the vapor pressure. The vapor pressure of water at 20º C (68º F) is 2.34 kN/m^2 (0.339 psi). Pressure conversion factors are given in Table 1-1.

Table 1-1.
Pressure Conversion Factors.

10^3 N/m^2	=	1 kPa
1 psi	=	6.895 kPa
12 inches of water (at 4^{o}C)	=	0.433 psi
1 inches of water (at 4ºC)	=	1.87 mm Hg
29.92 inches of Hg	=	1 Atmosphere

1.4.2.3. *Henry's Law Constant.* Henry's Law determines the extent of volatilization of a contaminant dissolved in water. Henry's Law states: The amount of any gas that will dissolve in a given volume of liquid, at constant temperature, is directly proportional to the pressure that the gas exerts above the liquid. Henry's Law is presented in the formula:

$$P_A = H_A \times X_A$$

where

P_A = partial pressure of compound A in the gas phase
H_A = Henry's constant of compound A
X_A = mole fraction of compound A in liquid phase in equilibrium with the gas phase.

Henry's constant quantifies the tendency for a volatile in landfill leachate to partition to the vapor phase. This constant is temperature-dependent, increasing with increasing temperature. Estimates of vapor pressure and Henry's constant for numerous organic compounds are shown in EM 1110-1-4001, Soil Vapor Extraction and Bioventing. Additional information on Henry's constant can be found in DG 1110-1-3 Air Stripping.

1.4.3. *Biological Decomposition.* Sanitary landfills produce large quantities of gas, with the major components being methane (CH_4) and carbon dioxide (CO_2). LFG generation occurs as a result of two conditions, aerobic and anaerobic decomposition and can be divided into three distinct phases, however, it is important to understand that there will be both aerobic and anaerobic degradation occurring at the same time.

1.4.3.1. *Phase 1—Aerobic Decomposition.* During the aerobic decomposition phase, microorganisms slowly degrade the complex organic portions of the waste using the O_2 trapped during the landfilling process to form simpler organic compounds, CO_2, and water. Aerobic decomposition begins shortly after the waste is placed in the landfill and continues until all of the entrained O_2 is depleted from the voids and from within the organic waste. Aerobic bacteria produce a gas characterized by high temperatures, high CO_2 content (30 percent), and low CH_4 content (2 to 5 percent).

Aerobic decomposition within the landfill typically lasts for several months, however, due to air exchange between the atmosphere and the landfill, there may always be some aerobic degradation occurring at the edges of the waste. Aerobic degradation generally degrades many of the larger polymers such as starches, cellulose, lignins, proteins, and fats into smaller, more available oligomers (polymer consisting of 2 to 4 monomers). These oligomers can then be further degraded into dimers (molecules consisting of two identical simpler molecules) and monomers such as sugars, peptides, amino acids, long-chain fatty acids, glycerol and eventually organic acids. These less complex products of aerobic degradation are more readily degraded anaerobically than the larger polymers.

1.4.3.2. *Phase 2—Anaerobic Decomposition.* Anaerobic decomposition occurs in two distinct phases. When all of the entrained O_2 is depleted from the waste, the waste decomposition changes from aerobic to anaerobic and two new groups of bacteria emerge which thrive in anaerobic environments. Facultative microbes convert the simple monomers into mixed acid products along with hydrogen and CO_2. Anaerobic bacteria convert the mixed volatile organic acids (e.g., formic, acetic, propionic and butyric acids), aldehydes and ketones into primarily acetic acid and hydrogen. These organic acids reduce the pH, which increases the solubility of some organics and inorganics, increasing the concentration of dissolved solids in the leachate. CH_4 production can be limited during this stage since the low pH (5 to 6) is somewhat toxic to methanogenic (methane-producing) bacteria.

1.4.3.3. *Phase 3—Anaerobic Decomposition.* In the next phase of decomposition, CH_4 forming bacteria utilize CO_2, hydrogen, and inorganic acids to form CH_4 gas and other products. During this stage of anaerobic decomposition, the methanogenic bacteria become more prominent. These methanogens degrade the volatile acids, primarily acetic acid and use hydrogen to generate CH_4 and CO_2. This degradation results in a more neutral pH (7 to 8) as the organic acids are consumed. A decrease in chemical oxygen demand (COD) and dissolved solids concentration within the leachate also occurs.

Phase 3 of the decomposition process is characterized by lower temperatures, high CO_2 concentrations (40 to 48 percent), and significantly higher CH_4 concentrations (45 to 57 percent). Anaerobic decomposition will continue until all of the volatile organic acids are depleted or until O_2 is reintroduced into the waste. Figure 1.1 shows landfill gas composition trends versus time for the aerobic and anaerobic decomposition of landfill refuse.

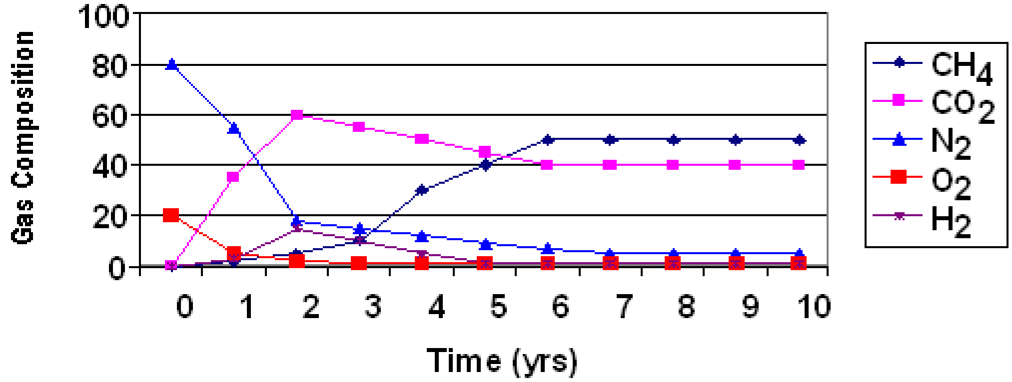

Figure 1.1. Landfill Gas Composition.

1.4.4. *Chemical Reactions*. Chemical reactions between materials in the waste can release gases. Most of these potential reactions are buffered by the presence of water. However, unpredictable reactions are possible with so many compounds potentially present. The heat generated from biological processes also tends to accelerate the release rate of compounds produced by chemical reactions.

1.5. Factors Affecting LFG Generation. Gas generation in landfills is affected by several factors:

- Waste composition.
- Temperature.
- Moisture.
- pH.
- Atmospheric conditions.
- Landfill cover.
- Waste density.
- Waste age.

1.5.1. *Waste Composition.* The primary nutrients (macronutrients) required for bacterial growth in a landfill are carbon, hydrogen, oxygen, nitrogen, and phosphorus. Small amounts of other elements (micronutrients) such as sodium, potassium, sulfur, calcium, and magnesium are also required for bacterial growth. The availability of macronutrients in the landfill mass has an affect on both the volume of leachate generated from microbial processes and the composition of the generated gases. Landfills that accept municipal wastes generally have an adequate nutrient supply for most microbial processes to proceed. Specialized landfills such as those at military installations that handle hazardous materials or munitions wastes only, may not have sufficient nutrients in the waste to sustain a large microbial population. The primary sources of macronutrients are yard wastes and food wastes. Micronutrient requirements are very small and can usually be met by the trace amounts found in wastes and/or leached from cover soils.

1.5.2. *Temperature.* The optimum temperature range for aerobic decomposition is 54 to 71ºC (130 to 160ºF), while the optimum temperature range for anaerobic bacteria is 30 to 41ºC (85 to 105ºF). A dramatic drop in activity of anaerobic bacteria has been noted at temperatures below 10ºC (50ºF).

1.5.3. *Moisture.* Moisture is needed for biological decomposition of waste. The moisture content of MSW as received typically ranges from 15 to 40 percent with an average of 25 percent. The moisture content can vary greatly in different zones of the landfill. Very low moisture content may prevent decomposition of waste and thus limit gas production. The optimum moisture content to maximize gas production is in the 50 to 60 percent range.

1.5.4. *pH.* The materials placed in a landfill can cause the pH of leachate within the landfill to vary widely. However, leachate is typically expected to be in the pH range of 5 to 9. The pH during CH_4 formation is generally in the range of 6.5 to 8.0. One concern during the acidic stages of the biological process (or any other time leachate within the landfill exhibits a low pH) is that the reduced pH will mobilize metals that may leach out of the landfill, or become toxic to the bacteria generating the gas.

1.5.5. *Atmospheric Conditions.* Atmospheric conditions affect the temperature, pressure, and moisture content within a landfill. Landfill covers and liners help to isolate waste from atmospheric conditions by limiting oxygen intrusion, limiting infiltration of precipitation, and buffering the effects of temperature changes.

1.5.5.1. *Temperature.* Cold climates will reduce biological activity in the surface layers, reducing the volume of gas generated. Deeper in the waste, the surface temperature affects are usually overcome by the heat generated by biological activity. The primary factors that affect temperature are waste depth, compacted density, microbial activity, chemical reactions, water content, and climate.

1.5.5.2. *Pressure.* Atmospheric pressure can have a minor affect on the rate at which landfill gas is released to the atmosphere. It can also influence the operation of gas extraction systems. A decrease in barometric pressure results in a temporary increase in LFG flow and an increase in barometric pressure will cause LFG flow to temporarily decrease. This is because the pressure within the landfill changes at a slower rate than the atmosphere and a pressure gradient temporarily develops between the inside and outside of the landfill until these pressures equalize.

1.5.5.3. *Precipitation.* Precipitation dramatically affects the gas generation process by supplying water to the process and by carrying dissolved O_2 into the waste with the water. High rates of precipitation may also flood sections of the landfill, which will obstruct gas flow. The amount of precipitation that reaches the waste is highly dependent on the type of landfill cover system.

1.5.6. *Density of the Waste.* The density of waste fills is highly variable. An estimate of waste density is often required for estimating landfill gas generation rates. Several reported density values are shown in Table 1-2. The reported values shown are for municipal solid waste:

Table 1-2.
Density of the Waste.

Waste Density kg/m^3 (lbs/cy)	**Reference**
474 to 711 (800 to 1200)	Stecker, Phillip, (1989). "Active Landfill Gas Recovery Systems," University of Wisconsin Sanitary Landfill Leachate and Gas Management Seminar, Madison, WI, December 4-7, 1989
650 (1100)	Emcon Associates (1980). "Methane Generation and Recovery from Landfills," Ann Arbor Science, Ann Arbor, Michigan
387 to 1662 (650 to 2800)	Landva, Arvid O., Clark, Jack I., (1990) "Geotechnics of Waste Fill," Geotechnics of Waste Fill – Theory and Practice, ASTM STP 1070, ASTM, Philadelphia, PA

1.5.7. *Age of Waste.* Once anaerobic conditions are established, landfill gas generation should be significant for 10 to 20 years or longer. Landfills that are several decades old are less likely to produce large quantities of landfill gas as most of the biological decomposition of the waste will have already taken place.

1.6. Transport Mechanisms. Transport of landfill gas occurs by the two principal mechanisms of diffusion and advection. Transport conditions both within the landfill and for the subsurface surrounding the landfill must be considered. These transport mechanisms are discussed in the following paragraphs.

1.6.1. *Diffusion.* Molecular diffusion occurs in a system when a concentration difference exists between two different locations. Diffusive flow of gas is in the direction in which its concentration decreases. The concentration of a volatile constituent in the LFG will almost always be higher than that of the surrounding atmosphere, so the constituent will tend to migrate to the atmosphere. Wind often serves to keep the surface concentration at or near zero, which renews the concentration gradient between the surface and the interior of the landfill and thus promotes the migration of vapors to the surface. Geomembranes in landfill covers will significantly reduce diffusion because the geomembrane prevents gases from diffusing to the atmosphere.

Specific compounds exhibit different diffusion coefficients. Diffusion coefficients are the rate constants for this mode of transport and quantify how fast a particular compound will diffuse. Published diffusion coefficients have been calculated using open paths between one vapor region (concentration) and another. This type of test is not very representative of the conditions found in a landfill. In landfills, gases must travel a tortuous path around all the solids and liquids in its path; thus, the published diffusion coefficients must be used with care.

1.6.2. *Advection*. Advective flow occurs where a pressure gradient exists. The rate of gas movement is generally orders of magnitude faster for advection than for diffusion. Gas will flow from higher pressure to lower pressure regions. In a landfill, advective forces result from the production of vapors from biodegradation processes, chemical reactions, compaction, or an active LFG extraction system. Variations in water table elevations can create small pressure gradients that either push gases out (rising tide) or draw gases in (falling tide). Changes in barometric pressure at the surface can also have an impact on the advective flow of gas.

1.7. Factors Affecting LFG Transport Mechanisms. LFG transport is affected by the following factors:

- Permeability.
- Geologic Conditions.
- Depth of groundwater.
- Man-made features.
- Landfill cover and liner systems.
- Barometric pressure.

1.7.1. *Permeability.* The permeability of waste has a large influence on gas flow rates and gas recovery rates. Coarse-grain wastes exhibit large values of gas permeability and more uniform gas flow patterns. By contrast, fine-grained and heterogeneous wastes are characterized by small values of gas permeability and gas flow patterns that are not uniform throughout the waste mass. Permeability of refuse is often reported in Darcys. One Darcy = 9.85×10^{-9} cm^2. Reported values for the apparent permeability of municipal solid waste are in the range of 13 to 20 Darcys. Water competes with air to occupy pore space within the solid matrix and ultimately reduces the effective porosity and ability of vapors to migrate through the landfill due to a reduction in available air pathways. This reduction will also reduce the rate of gas flow and decrease gas recovery rates.

1.7.2. *Geologic Conditions.* Geologic conditions must be determined to estimate the potential for off-site migration of gas. Permeable strata such as sands, gravels, and weathered bedrock provide a potential pathway for off-site migration, especially if these layers are overlain by a layer of low permeability soil. Geologic investigations must be performed to determine the potential for off-site migration. Additional attention must be given to areas where houses and other structures are present to ensure off-site migration will not impact these structures.

1.7.3. *Depth to Ground Water.* The water table surface acts as a no-flow boundary for gas. As a result, it is generally used to help estimate the thickness of the zone through which gas can travel. A consistently high ground water table will significantly reduce the potential for off-site migration of gas. The depth to groundwater (as well as seasonal variations) also needs to be evaluated during the design process to evaluate well construction requirements and the potential for water table upwelling (i.e., the upward rise of the water table toward a vacuum well screened in the unsaturated zone). EM 1110-1-4001 Soil Vapor Extraction and Bioventing provides a detailed discussion of upwelling.

1.7.4. *Man-Made Features.* In some instances, underground utilities such as storm and sanitary sewers or the backfill that surrounds these features may produce short-circuiting of airflow associated with an active landfill gas collection system. As a result, airflow may be concentrated along these features rather than within the landfill. Man-made features also provide a potential pathway for the off-site migration of landfill gas.

1.7.5. *Landfill Cover and Liner Systems.* The components of many hazardous and solid waste landfill cover systems consist of a vegetated surface component, a drainage layer, and a low permeability layer composed of one or more of the following: geomembrane, geosynthetic clay liner (GCL), or compacted clay. A geomembrane in the cover system will prevent the intrusion of air into the waste. Therefore, a higher operating vacuum can be applied to the gas collection system without the danger of overdrawing. Thus, the effective radius (reach) of influence of each well is increased. Overdrawing occurs when oxygen from the atmosphere is pulled into the landfills interior during the anaerobic phase.

Landfill liner systems consist of various combinations of low permeability layers and leachate collection layers. The low permeability layers are created using natural low permeability geologic formations, compacted clay, geomembranes, and geosynthetic clay liners. Liner systems prevent the migration of LFG to the surrounding areas. Liner systems also prevent gases in the surrounding geologic formations from being pulled into the LFG collection system.

1.7.6. *Barometric Pressure.* The amount of gas escaping from a landfill's surface changes as barometric pressure changes. Gas generation within a landfill will result in a positive pressure gradient from the inside to the outside of the landfill. For a passive LFG collection system, increases in atmospheric pressure will cause a decrease in gas flow from a landfill because the pressure differential between the inside and the outside has decreased. For an active gas collection system, there is a higher probability of atmospheric air intrusion through the landfill cover during periods when the barometric pressure is rising. The amount of air intrusion will be greatly affected by the type of cover on the landfill. A landfill with a low permeability (geomembrane) cover will be more resistant to air intrusion than a landfill with a soil cover.

1.8. **LFG Characteristics.** Landfill gas is typically a combination of methane, carbon dioxide, and non-methanogenic organic compounds. The table 1-3 shows characteristics of some of the typical components of landfill gas:

Table 1-3.
Landfill Gas Characteristics.

Constituent	Relative Specific Gravity	Concentration in Landfill Gas	Notes
Air	1	NA	Forms explosive mixture with methane
Methane	0.554	40-70%	Explosive; LEL 5% in air; UEL 15% in air
Carbon Dioxide	1.529	30-60%	Forms weak acid; Asphyxiant
Hydrogen Sulfide	1.19	800 ppm	Forms strong acid Toxic: PEL = 10 STEL = 15
Water Vapor	0.62	100% Saturated	Forms acids with hydrogen sulfide and carbon dioxide
Benzene	2.8	30 ppm	Flammable Toxic: PEL 1.0 ppm STEL 5 ppm
Toluene	3.1	300 ppm	Toxic: PEL 100 ppm STEL 150 ppm
Organic Acids	GT 2	Traces	Odorous
Organosulphur Compounds	GT 1.5	50 ppm	Odorous

LEL = lower explosive limit; UEL = upper explosive limit; STEL = short-term-exposure limit; PEL = permissible exposure limit.

1.8.1. ***Density and Viscosity.*** The density of LFG depends on the proportion of gas components present. For example, a mixture of 10 percent hydrogen and 90 percent carbon dioxide, such as might be produced in the first stage of anaerobic decomposition, will be heavier than air, while a mixture of 60 percent methane and 40 percent carbon dioxide, such as might be produced during the methanogenic phase of decomposition, will be slightly lighter than air. Some typical values for density and viscosity at 0^{o} C (32^{0} F) and atmospheric pressure are given in Table 1-4.

Table 1-4.
Typical Values for Gas Density and Viscosity at 0^{o}C and Atmospheric Pressure

Gas	Density (kg/m^3)	Viscosity (Pa*s)
Air	1.29	1.71×10^{-5}
Methane	0.72	1.03×10^{-5}
Carbon Dioxide	1.9	1.39×10^{-5}
50% CH_4 + 50% CO_2	1.35	1.21×10^{-5}
60% CH_4 + 40% CO_2	1.19	1.17×10^{-5}

1.8.2. *Heat Value Content.* During the methanogenic stage, LFG can be expected to have a heating value of 500 Btu/ft^3 under good conditions. This value is about half that of natural gas. The actual heating value of the gas from a landfill is a function of the type age of the waste, the type of landfill cover, and many other factors that have been discussed previously in this section.

1.8.3. *Non-Methane Organic Compounds.* If a landfill contains a significant amount of municipal solid waste, the gas produced will consist of approximately 50 percent methane, 50 percent carbon dioxide, and trace amounts of non-methane organic compounds (NMOC). The concentration of NMOCs can range from 200 to 15,000 ppm according to research from the EPA. In the EPA study, ethane, toluene, and methylene chloride were found at the highest concentrations in landfill gas with average reported values of 143, 52, and 20 ppm, respectively. The most frequently detected compounds reported were trichloroethene, benzene, and vinyl chloride. During the design phase of a landfill closure, historical records or word of mouth information should be obtained as to the type of wastes that were placed in the landfill and the potential for these wastes to create off-gas emissions.

1.8.4. *Water Vapor.* Gas created during the decomposition of organic compounds typically includes between 4 and 7 percent by volume water vapor. The actual water vapor content of LFG will depend on the temperature and pressure within the landfill. Temperatures are typically elevated over ambient during biological decomposition, increasing the evaporation of water into the LFG.

1.8.5. *Others.* Hydrogen is produced during waste decomposition, particularly during the initial anaerobic conversion of mixed organic acids to acetic acid. Significant amounts of hydrogen are later consumed in the formation of CH_4. Hydrogen is flammable between 4 and 74 percent, by volume, in air. The presence of CO_2 affects these ranges although little significant change occurs near the lower limit of the range.

1.9. **LFG Condensate**.

1.9.1. *Source of Landfill Gas Condensate.* Gas condensate forms in the collection and processing systems as the gas undergoes changes in temperature and pressure. As LFG moves through the collection system, the gas cools and the various constituents condense out of the gas. The condensed liquid is composed principally of water, organic compounds, and traces of inorganics such as particulate matter. The organic compounds are often not soluble in water and may separate from the aqueous phase. Most active LFG collection systems include a series of condensate collection pots that remove a portion of the entrained water from the gas prior to entering the vacuum pump or blower.

1.9.2. *Condensate Quality.* The quality of gas condensate is a function of:

- Nature of the waste.
- Age of the waste.
- Moisture content.
- Temperature.

- Landfill size and configuration.
- Liner and/or cover materials.
- Climatic conditions.

Organic contaminants frequently found in landfill gas condensate (Table 1-5).

Table 1-5.
Organic Contaminants.

Benzene	2-Butanone (MEK)	1,4-Dichlorobenzene
Toluene	Carbon Tetrachloride	2,4-Dinitrotoluene
Phenol	Vinyl Chloride	Hexachlorobenzene
Ethyl Benzene	4-Methylphenol	Hexachlorobutadiene
Benzyl Alcohol	Chlorobenzene	Hexachloroethane
Bis (2-Chloroisopropyl) ether	Chloroform	Nitrobenzene
Bis (2-ethylhexyl) phthalate	1,2-Dichloroethane	Pentachlorophenol
Napthalene	1,1-Dichloroethene	Pyridine
N-nitrosodimethylamine	Tetrachloethylene	2,4,5-Trichlorophenol
2,4-Dimethylphenol	Trichloethylene	2,4,6-Trichlorophenol