



PDHonline Course C654 (3 PDH)

Landfill Gas Collection O & M

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2020

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CHAPTER 1 Introduction

1.1. Purpose and Scope. This Engineering Manual (EM) establishes criteria and guidance for landfill gas (LFG) collection and treatment systems. The foundation of Corps of Engineers environmental work is the Environmental Operating Principles as specified in ER 200-1-5. These seven tenets serve as guides and must be applied in all Corps business lines as we strive to achieve a sustainable environment.

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

1.3. Distribution Statement. Approved for public release; distribution unlimited.

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

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

- a. Reasons for LFG control;
- b. LFG generation mechanisms;
- c. LFG and condensate characteristics;
- d. Estimation of LFG production and emissions;
- e. LFG collection and treatment design considerations;
- f. Operation and maintenance (O&M) requirements for LFG collection and treatment systems; and
- g. Regulatory requirements.

1.5.1. Reasons for LFG Control. The following is a list of common reasons for controlling the LFG produced by a landfill:

- a. Prevent air pollution and comply with regulatory air emission criteria;
- b. Reduce hazards due to off-site migration;
- c. Prevent damage to the landfill cover slope stability;
- d. Odor control;
- e. Energy recovery; and

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f. Prevent vegetation distress.

1.5.2. LFG Generation Mechanisms. LFG is produced by the biological decomposition of general solid waste refuse and other organic materials disposed of in the landfill. LFG production typically begins within a year of waste placement, and may continue up to 50 years after landfill closure, with peak LFG production for any given disposal cell occurring within the first or second year of waste placement. The total LFG production rate increases as more waste is added to the landfill. Reported LFG production rates vary from 0.0007 to 0.080 cubic meters of LFG per kilogram of waste burial per year (USEPA, 2005a).

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

1.5.2.1. 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.

1.5.2.2. 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 20°C (68°F) is 2.34 kN/m² (0.339 psi). Pressure conversion factors are given in Table 1-1.

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

1.5.2.3. 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 LFG 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 vapor phase

H_A = Henry's constant of compound A

X_A = mole fraction of compound A in liquid phase in equilibrium with the vapor 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 200-1-18, "Soil Vapor Extraction and Bioventing". Additional information on Henry's constant can be found in DG 1110-1-3 "Air Stripping".

1.5.3. Biological Decomposition. Sanitary landfills produce large quantities of LFG, with the major components being methane and carbon dioxide. 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.

1.5.3.1. Phase 1 Aerobic Decomposition.

1.5.3.1.1. During the aerobic decomposition phase, microorganisms slowly degrade the complex organic portions of the waste using the oxygen trapped during the landfilling process to form simpler organic compounds, carbon dioxide, and water. Aerobic decomposition begins shortly after the waste is placed in the landfill, and continues until all of the entrained oxygen is depleted from the voids and from within the organic waste. Aerobic bacteria produce a LFG characterized by high temperatures, high carbon dioxide content (30 percent), and low methane content (2 to 5 percent). Interior landfill temperatures can run between 90 and 120 °F

1.5.3.1.2. 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.

1.5.3.2. Phase 2 Anaerobic Decomposition . Anaerobic decomposition occurs in two distinct phases. When all of the entrained oxygen 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 carbon dioxide. 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. Methane production can be limited during this stage, since the low pH (5 to 6) is somewhat toxic to methanogenic (methane-producing) bacteria.

1.5.3.3. Phase 3 Anaerobic Decomposition .

1.5.3.3.1. In the next phase of decomposition, methane producing bacteria utilize carbon dioxide, hydrogen, and inorganic acids to form methane 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 methane and carbon dioxide. 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.

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

1.5.4. Chemical Reactions. Chemical reactions between materials in the waste can release LFG. 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.

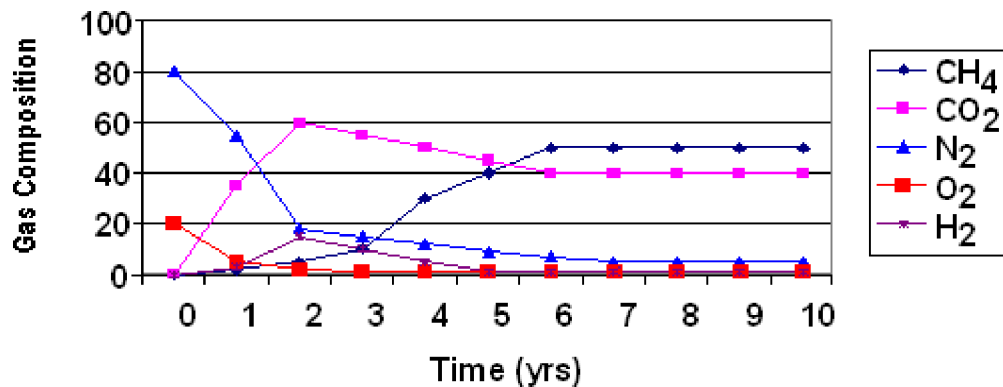


Figure 1.1. LFG Composition.

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

- a. Waste composition;
- b. Temperature;
- c. Moisture;
- d. pH;
- e. Atmospheric conditions;
- f. Landfill cover;
- g. Waste density; and
- h. Waste age.

1.6.1. 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 LFG. 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 high organic wastes such as yard wastes, food wastes, and sewage sludge. Micronutrient requirements are very small and can usually be met by the trace amounts found in wastes and/or leached from cover soils.

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

1.6.3. Moisture. Moisture is needed for biological decomposition of waste. The moisture content of municipal solid waste (MSW) as received typically ranges from 15% to 40% 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 LFG production. The optimum moisture content to maximize LFG production is in the 50% to 60% range.

1.6.4. 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 methane 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 LFG.

1.6.5. 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.

1.6.5.1. Ambient Temperature. Cold climates will reduce biological activity in the surface layers, reducing the volume of LFG generated. Deeper in the waste, the surface temperature effects 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.

1.6.5.2. Pressure. Atmospheric pressure can have a minor affect on the rate at which LFG is released to the atmosphere. It can also influence the operation of LFG 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.

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

1.6.6. Density of the Waste. The density of waste fills is highly variable. An estimate of waste density is often required for estimating LFG generation rates. Several reported density values are shown in Table 1-2. The reported values shown are for MSW:

Table 1-2. Density of the Waste	
Waste. Density kg /m (lbs/cy)	Reference
474 to 711 (800 to 1200)	Stecker, Phillip, (1989). "Active 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

1.6.7. Age of Waste. Once anaerobic conditions are established, LFG 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 LFG, since most of the biological decomposition of the waste will have already taken place.

1.7. Transport Mechanisms. Transport of LFG 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.

1.7.1. Diffusion.

1.7.1.1. Molecular diffusion occurs in a system when a concentration difference exists between two different locations. Diffusive flow of LFG 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 LFG from diffusing to the atmosphere.

1.7.1.2. 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, LFG must travel a tortuous path around solids and liquids in its waste burial path; thus, the published diffusion coefficients must be used with care.

1.7.2. Advection. Advective flow occurs where a pressure gradient exists. The rate of LFG movement is generally orders of magnitude faster for advection than for

diffusion. LFG 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 LFG.

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

- a. Permeability;
- b. Geologic conditions;
- c. Depth to groundwater;
- d. Man-made features;
- e. Landfill cover and liner systems; and
- f. Barometric pressure.

1.8.1. Permeability. The permeability of waste has a large influence on LFG flow rates and LFG recovery rates. Coarse-grain wastes exhibit large values of permeability and more uniform LFG flow patterns. By contrast, fine-grained and heterogeneous wastes are characterized by small values of permeability and LFG flow patterns that are not uniform throughout the waste mass. Permeability of refuse is often reported in Darcys. One Darcy = $9.85 \times 10^{-8} \text{ cm}^2$. Reported values for the apparent permeability of MSW 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 LFG flow and decrease recovery rates.

1.8.2. Geologic Conditions. Geologic conditions must be determined to estimate the potential for off-site migration of LFG. 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.

1.8.3. Depth to Ground Water. The water table surface acts as a no-flow boundary for LFG. As a result, it is generally used to help estimate the thickness of the zone through which LFG can travel. A consistently high ground water table will significantly reduce the potential for off-site migration of LFG. 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 200-1-18 "Soil Vapor Extraction and Bioventing" provides a detailed discussion of upwelling.

1.8.4. 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 LFG 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 LFG.

1.8.5. Landfill Cover and Liner Systems.

1.8.5.1. 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 LFG 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.

1.8.5.2. 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 (GCLs). 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.

1.8.6. Barometric Pressure. The amount of LFG escaping from a landfill's surface changes as barometric pressure changes. LFG 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 LFG flow from a landfill because the pressure differential between the inside and the outside has decreased. For an active LFG 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.

1.9. LFG Characteristics. LFG is typically a combination of methane, carbon dioxide, and non-methane organic compounds (NMOCs). The table 1-3 shows characteristics of some of the typical components of LFG:

1.9.1. Density and Viscosity. The density of LFG depends on the proportion of individual gas components present. For example, a mixture of 10% hydrogen and 90% carbon dioxide, such as might be produced in the first stage of anaerobic decomposition, will be heavier than air, while a mixture of 60% methane and 40% 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 C (32 ° F) and atmospheric pressure are given in Table 1-4.

Table 1-3. LFG Characteristics			
Constituent	Relative Specific Gravity	Concentration in LFG	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.			

1.9.2. Heat Value Content. During the methanogenic stage, LFG can be expected to have a heating value of 500 Btu/ft³ under good conditions. This value is about half that of natural LFG. The actual heating value of the LFG 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.

1.9.3. Non-Methane Organic Compounds. If a landfill contains a significant amount of MSW (i.e., general household and consumer refuse), the LFG produced will consist of approximately 50% methane, 50% carbon dioxide, and trace amounts of NMOCs. The concentration of NMOCs can range from 200 to 15,000 parts per million (ppm) according to research from the USEPA. NMOCs can originate as constituents of various types of consumer and small volume maintenance products disposed of in the MSW, or may be generated as biological and chemical degradation daughter products. Benzene, toluene, ethyl benzene and total xylenes (BTEX) can originate from the disposal of fuel and other petroleum-based and automotive products. NMOC concentrations could be higher if non-hazardous or hazardous industrial wastes were historically disposed of in the MSW landfill. In the

USEPA study, ethane, toluene, and methylene chloride were found at the highest concentrations in LFG, with average reported concentrations 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 LFG emissions.

Table 1-4.		
Typical Values for Density and Viscosity at 0 ° C and Atmospheric Pressure		
Vapor Constituent	Density (kg/m³)	Viscosity (Pa*s)
Air	1.29	1.71 X 10 ⁻⁴
Methane	0.72	1.03 X 10 ⁻⁴
Carbon Dioxide	1.9	1.39 X 10 ⁻⁴
50% CH ₄ + 50% CO ₂	1.35	1.21 X 10 ⁻⁴
60% CH ₄ + 40% CO ₂	1.19	1.17 X 10 ⁻⁴

1.9.4. Water Vapor. LFG 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.

1.9.5. 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 methane. Hydrogen is flammable between 4% and 74% by volume in air. The presence of carbon dioxide affects these ranges although little significant change occurs near the lower limit of the range.

1.10. LFG Condensate Characteristics.

1.10.1. Source of LFG Condensate. Condensate forms in the LFG collection and processing systems as the vapor phase undergoes changes in temperature and pressure. As LFG moves through the collection system, the vapor phase cools and the various constituents condense out. 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 LFG prior to entering the vacuum pump or blower.

1.10.2. Condensate Quality. The quality of LFG condensate is a function of:

EM 200-1-22

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- a. Nature of the waste;
- b. Age of the waste;
- c. Moisture content;
- d. Temperature;
- e. Landfill size and configuration;
- f. Liner and/or cover materials; and
- g. Climatic conditions.

Volatile organic compounds (VOCs) frequently found in LFG condensate are listed in Table 1-5 below:

Benzene	2-Butanone (MEK)	1,4-Dichlorobenzene
Toluene	Carbon tetrachloride	2,4-Dinitrotoluene
Phenol	Vinyl chloride	Hexachloro benzene
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-Di methyl phenol	Trichloethylene	2,4,6-Trichlorophenol

CHAPTER 2 Investigations

2.1. Site Characterization and Estimation of Landfill Gas Emissions. Site inspections, data review, and interviews should be performed to gather preliminary information about a landfill. Important preliminary information includes the following:

- a. Size and depth of the landfill;
- b. Nature of the waste and the potential for producing methane and other gases;
- c. Age of the waste;
- d. Type of cover and liner present;
- e. Existing landfill gas (LFG) collection and monitoring systems;
- f. Hydrogeologic conditions surrounding the landfill; and
- g. Location and number of adjacent buildings.

2.1.1. General. After preliminary information has been gathered, a decision needs to be made about how much additional information should be gathered in order to estimate the amount of LFG being generated and whether or not it is migrating off-site. The following paragraphs describe methods of site characterization, quantifying LFG production, and the potential for off-site migration. The work flow diagram presented below (excerpted from USEPA, 2005a) provides a visualization of the LFG evaluation process, with the remainder of this section focused on the LFG sampling and data analysis steps.

2.1.2. Landfill Characteristics. Physical investigations of the nature of the wastes within the landfill are rarely undertaken due to the heterogeneity of landfills and the difficulty of collecting representative samples from within a landfill. Preliminary information about the type and age of the wastes within the landfill should provide a good indication as to the amount and type of gases that will be generated. If additional information is required, soil gas surveys and pump tests can be used to better quantify the amount and types of LFG being produced. Soil gas surveys and pump tests are described later in this section.

2.1.3. Hydrogeologic Conditions.

2.1.3.1. The migration of LFG off-site is greatly affected by the geologic conditions at the site. High permeability materials such as sands, gravels, and fractured or weathered bedrock transmit vapors very effectively. Low permeability layers such as silts and clays have smaller pore sizes and do not transmit LFG as readily. These zones also retain higher moisture levels due to capillary forces and that pose an additional barrier to LFG flow. High permeability layers in contact with

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landfills are capable of transmitting LFG over large distances, especially when these units are overlain by a continuous layer of low permeability material.

2.1.3.2. Hydrogeologic investigations must be performed to determine the geologic conditions, ground water table elevation, and potential paths for LFG to escape. EM 1110-1-1804, "Geotechnical Investigations", EM 1110-1-1802, "Exploration for Engineering and Environmental Investigations," and EM 200- 1-17, "Monitor Well Design, Installation, and Documentation at H TRW Sites" provide general information on performing field investigations and well installation. Table 2-1 lists important parameters that should be determined when investigating the off-site migration of LFG.

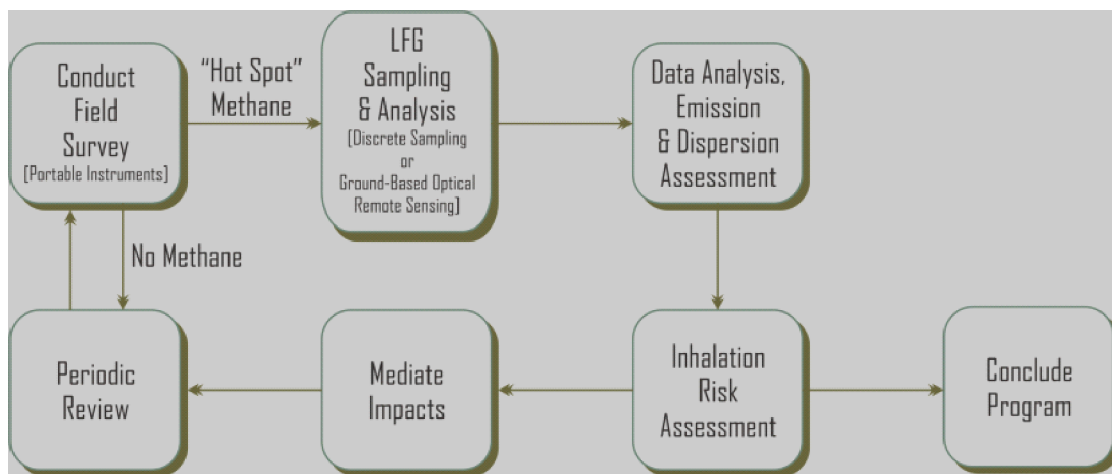


Figure 2.1. Data Gathering and Decision-Making Flow Chart for the Evaluation of LFG Emissions

Table 2-1. Important Parameters the Affect Off-Site Migration of LFG		
Parameter	Collection Method	Reference
Stratigraphy	Soil borings	EM 1110-1-1804 ASTM D 2487 ASTM D 2488
Depth to ground water	Monitoring wells	EM 200-1-17
Heterogeneity/utility trenches	Geophysical investigations	EM 1110-1-1804
Moisture content	Soil borings	ASTM D 2216
Grain size/porosity	Soil borings	ASTM D 422
Atterberg limits	Soil borings	ASTM D 4318
Vapor phase concentrations	LFG monitoring probes	EM 200-1-18

2.1.4. Ambient Air Quality. Ambient air quality monitoring may be necessary to determine the need for a LFG collection system. A typical monitoring program would include the collection of air samples at pre-determined locations based on

meteorological conditions at the site over an appropriate time period (8 hours, 24 hours, etc.). Current state-of-the-art techniques for evaluating ambient air concentrations and emissions from municipal solid waste (MSW) landfills include infrared radial surface mapping techniques using optical remote sensing. These techniques are very sophisticated and not likely applicable for most Army landfills, so they are not discussed in this EM. Refer to USEPA (2005a) and BCME (2010) for comprehensive discussions of these infrared mapping techniques, along with more sophisticated sampling strategies and statistical analysis. Ambient conditions, including temperature, barometric pressure, and precipitation events, should be recorded. Vapor phase parameters analyzed may include methane, hydrogen sulfide, and non-methane organic compounds (NMOCs).

2.1.5. LFG Monitoring Probes. LFG monitoring probes can be used during the investigation phase or for long-term monitoring to determine if LFG is migrating off-site through the subsurface. LFG probes should be installed in the more permeable strata between the landfill unit and either the property boundary or structures where LFG migration may pose a problem. Multiple or nested probes are useful in defining the vertical configuration of the migration pathway (refer to EM-200-1-18, "Soil Vapor Extraction and Bioventing" for use and construction of nested probes). Probe location and spacing is dependent of geologic conditions, water table conditions, and adjacent property use. LFG monitoring probe design and construction requirements are discussed in later sections of this EM.

2.1.6. Monitoring LFG in Structures. Basements and crawl spaces of buildings located near landfills are potential collection points for methane and other gases. Methane that collects in these confined spaces can create a potential explosion hazard. Basements and crawl spaces of buildings located in the vicinity of landfills should be monitored for LFG during the investigative phase, which is typically done using an explosimeter, flame ionization detector (FID), and/or various ambient air sampling techniques for laboratory analysis.

2.1.7. Soil Gas Surveys. Soil gas surveys can provide information about the production and migration of LFG, and are less costly and require considerably less field time than alternative sampling methods such as the installation of soil gas monitoring probes. Soil gas surveys can be either active or passive in nature. They can be used to collect information on methane and other volatile organic compound (VOC) emissions from a landfill. The data collected can be used for several purposes:

- a. Characterization of LFG composition as an indicator of the nature of the waste or to determine the health risk posed by the vapor phase constituents;
- b. Design of LFG collection and treatment systems;
- c. Identification of LFG migration; and/or

d. Assessment of the vapor intrusion pathway at landfills where LFG may be migrating into buildings.

2.1.7.1. Sampling Depths. Vapor phase concentrations diminish near the landfill surface due to diffusion into the atmosphere and advective exchange of air from the atmosphere. Generally, more concentrated vapors are found at depth, although concentrations vary significantly due to proximity to sources and preferred lateral migration pathways. Soil gas samples for characterization of LFG composition and design of collection and treatment systems should be taken at least three feet below the surface. In many cases, obstructions will prevent penetration of the sampling probe to the required depth and offset sampling locations will be required. Deeper sampling depths are appropriate where the waste layer is thick. When sampling for LFG migration, the depth of the sampling probe/well may be dictated by regulation, but should consider the depth of preferred migration pathways, based on the stratigraphy at the site, and the nature of potential exposure such as basements or manmade features.

2.1.7.2. Plan Location. The number and location of soil gas sampling points is dependent on the subsurface heterogeneity of both vapor flow paths and vapor sources. For characterization of LFG composition, the sampling locations should encompass the entire landfill. The density of sampling points should be increased in areas of the landfill where the waste thickness is greatest and in known source areas. For perimeter monitoring of LFG migration, the spacing of sample collection points may be dictated by regulation, but should consider the scale of heterogeneity in potential LFG migration pathways. Monitoring points are typically spaced every 100 to 500 feet around the perimeter of the landfill.

2.1.7.3. Sampling Methods. There are two primary means to collect subsurface vapor samples; active soil gas sampling and passive (non-pumping, sorbent) sampling. In addition, surface flux measurements can also be made. Samples can be collected on a grab real-time basis or using time-integrated sampling devices and protocol that incrementally collect a soil gas sample over an extended period of time (e.g., 24 hours). The following paragraphs describe each to these methods.

2.1.7.3.1. Active Soil Gas Sampling. Active soil gas sampling requires that samples of the actual soil gas filling the pore spaces in the subsurface be collected and analyzed. This method is most appropriate for gathering data on concentrations for LFG treatment system design, as well as the quantification and determination of risk posed by the LFG migration to receptors. These samples represent a snapshot of the LFG concentrations and are, therefore, susceptible to variations due to changes in barometric pressure, LFG generation rates, and precipitation events. Sampling requires placement (either temporary or permanent) of a probe or well into the subsurface. This can be accomplished by direct-push methods or a drill rig.

Drilling into a landfill requires additional safety precautions, and should be performed in accordance with EM 385-1-1, '6 DIHty DQC[+HDQM[5 HTXLLHP HQtN , " including preparation of a hazard task analysis. In some cases, slide hammers or similar devices can be used if the material into which the probe is to be placed poses little resistance.

2.1.7.3.1.1. Typically, decontaminated steel or PVC pipe/probes are used for temporary sampling probes, although drive tips connected to teflon tubing can be used, as can driven casing (e.g., using sonic or dual-tube casing hammer rigs - packers are placed in the casing to reduce the volume of air needed to be removed). Permanent probes are often installed in a manner similar to ground water monitoring wells and can be constructed of steel or PVC. Well seals that prevent intrusion of ambient air entry are critical. Refer to EM 200-1-18, ' Soil Vapor Extraction and Bioventing . (Chapter 5) for more information on well/probe construction. Once installed, the probe or well is sampled by drawing a vacuum on the well using a vacuum pump and purging the well of several well volumes of soil gas. Typically, three to five times the well volume is purged. Monitoring of vapor concentrations as purging progresses can indicate the ideal amount of purging (e.g., stabilization of field screening measurements), but three well volumes is typically a minimum.

2.1.7.3.1.2. Actual sampling depends on the required container for the sample. Summa canisters can be used directly and are the proper choice for off-site analysis, but glass gas-tight syringes or Tedlar bags can be used for on-site field screening or analysis where short-term storage is involved. Care must be taken to avoid leakage of atmospheric air into the sample container during placement or removal of the sample container to/from the air stream. Refer to ASTM D5314 for more information on proper sampling methods. Upon completion of sampling, temporary probes are typically removed. The hole should then be sealed with grout or bentonite. Unnecessary permanent probes should be decommissioned in accordance with state regulation. Refer to EM 200-1-17, ' Monitoring Well Design, Installation, and Documentation at HTRW Sites . for additional information on well decommissioning requirements.

2.1.7.3.2. Passive Soil Gas Sampling . Passive soil gas sampling techniques allow the sorption of the soil gas vapors onto activated carbon or similar material over some period of time. The sorbent material is later collected and submitted for thermal desorption and analysis. These methods do not allow the quantification of the soil gas concentrations unless flow is directed and measured through the sorptive cartridge or filter. This technique is most appropriate for qualitatively identifying the locations of contaminant sources or composition of the soil gas. These techniques allow a longer exposure to the soil gas, and are therefore less susceptible to variations due to barometric pressure changes, LFG generation rates, and precipitation events. Different vendors have different materials and placement methods. In some cases, the sorbent material is enclosed in an inverted glass vial or moisture resistant fabric and buried at depth in the soil for later retrieval. Other

vendors have materials that are set under a stainless steel cover at the ground surface. The materials are placed and left for some period of time (typically days to weeks) before retrieval. Proper retrieval requires the filling of any holes created as part of the survey.

2.1.7.3.3. Surface Flux Measurements. In some cases, there is a need to determine the amount and concentrations of LFG escaping to the surface. Flux chambers are used to quantify the mass of contaminants emanating from the subsurface. These chambers are boxes or domes open on the bottom and typically 0.5 - 1 m in lateral dimension. They are set at the ground surface with the open side set into the soil a small distance to provide an adequate seal. A carrier gas is introduced into the chamber on one side and collected into a Summa canister or similar container on the other side. The flux of the carrier gas is known and the chamber is left in place for a period of time. The concentration of the contaminants in the collected soil gas is determined and the mass of contaminants is calculated. The rate of mass emissions is then computed based on the time the chamber was in place.

2.1.8. Pump Tests. Pump tests can be performed to estimate LFG production. To perform a pump test, one or more extraction wells are installed and a blower is used to extract LFG. Based on LFG composition, landfill pressures, and flow measurements, the LFG production rate is calculated. LFG monitoring probes are used to estimate the radius of influence. Experience has shown the difficulty of accurately correlating pump test results with long-term LFG recovery, particularly at small landfills. Pump tests are, therefore, not normally recommended except for sites with the potential to produce large amounts of LFG over an extended period of time. Additional information on pump tests can be found in *Methane Generation and Recovery from Landfills* (Emcon and Associates, 1980). In addition, USEPA Method 2E, *Determination of Gas Production Flow Rate* can be used to calculate the flow rate of NMOCs from landfills. This method indicates that extraction wells should be installed either in a cluster of three or at five dispersed locations in the landfill. A blower is then used to extract LFG from the landfill. LFG composition, landfill pressures, and orifice plate pressure differentials (correlates to total LFG flow rate) from the wells are measured, which then allows the LFG production flow rate to be calculated from this data. USEPA Method 2E can be found in 40 CFR Part 60, Appendix A or at the following web site: <http://www.epa.gov/ttn/emc>.

2.1.9. Analytical Methods. The determination of the appropriate analytical methods is very project specific and depends on the project objectives, data quality objectives, and nature and concentration of contaminants of interest. The project chemist must be consulted to assure appropriate methods are chosen. Analysis can be conducted in the field using portable equipment or in a fixed lab.

2.1.9.1. Field Analyses.

2.1.9.1.1. Field screening analyses can be used to determine an initial estimate of conditions at the site. Field screening analyses are also used for periodic monitoring during the operation and maintenance phase of the project to determine what adjustments need to be made to the LFG collection and treatment system.

2.1.9.1.2. Infrared instruments are typically used to monitor gases (methane and carbon dioxide) below grade, while explosimeters are typically used to monitor potential explosive atmospheres above grade. A photoionization detector (PID) or colorimetric indicator tubes may also be used to monitor for certain NMOCs at above grade locations. The use of field portable GCs and GC/MSs is acceptable if there is a need to identify and accurately quantify specific NMOCs; however, these instruments must be operated by a trained analyst. For field GC or GC/MS work, and sometimes for other methods, some degree of quality control/quality assurance is often required, including analysis of duplicates, spikes, and blanks.

2.1.9.2. Fixed Laboratory Analyses. For definitive analyses, samples are sent to off-site labs and analyzed according to specified methods. Summa canisters are typically used to assure representative samples arrive at the lab. A chemist should be consulted for proper selection and coordination with an off-site lab. Additional information on test methods for air samples can be found in EPA/625/R-96/010b, Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air. This document describes Method TO-14A, which is a procedure for sampling and analysis of VOCs in ambient air. The method was originally based on collection of air samples in Summa canisters, but has now been generalized to other specially prepared canisters. USEPA Method TO-15 is similar to USEPA Method TO-14A, but involves an expanded list of VOCs that can be analyzed (e.g., ketones).

2.1.10. Data Analysis. The evaluation of the results is dependent on the sampling objectives. The characterization of potential sources typically involves the qualitative evaluation of the data looking primarily for the locations of the highest "hits". The analysis of the data for risk assessment purposes may involve statistical analysis, such as computation of the mean and upper confidence limit based on multiple data points. LFG migration pathways are determined based on the samples and the waste/stratigraphy in the area of vapor detections in the perimeter probes. For design of treatment systems, the raw concentrations of LFG constituents are typically averaged over the area of the collection system.

2.2. Estimation of LFG Production and Emissions. LFG production and emissions are site-specific and a function of both controllable and uncontrollable factors. It is, therefore, difficult to accurately predict the rate of LFG emissions from a landfill. A summary of reported methane generation rates is provided in Table 3-1. One approach to predicting LFG generation from a MSW landfill is to employ a simplified

model that is consistent with fundamental principles. Several models are available for estimating the LFG generation rate using site-specific input parameters. The LandGEM model was developed by the USEPA to estimate LFG emissions and to determine regulatory applicability to Clean Air Act (CAA) requirements. There are also other LFG emission models in use by industry. The CAA regulations allow states the opportunity to use the results from models other than LandGEM. However, most of these models are proprietary, and are thus not as readily available as LandGEM. Regardless of what model is used, the accuracy of the inputs drives the results, and given the level of uncertainty associated with these inputs, it makes estimating landfill emissions very difficult.

2.2.1. LandGEM. LandGEM provides an automated estimation tool for quantifying air emissions from MSW landfills. The LandGEM estimation tool is set up in Excel spreadsheet format, and can be downloaded along with its user's manual from the following web site: <http://www.epa.gov/ttn>. There are two sets of default input values available for use in the LandGEM estimation tool. One input data set is for use in determining regulatory applicability and emission requirements under the Clean Air Act (CAA), which represents very conservative input values. The other input data set is less conservative, and can be used to produce typical emission estimates in the absence of site-specific test data, and is mostly based on emission factors contained in the USEPA's "Compilation of Emission Factors" (otherwise known as AP-42). Site-specific data can also be inputted into LandGEM. Once total LFG emissions are estimated, LandGEM can then be used to estimate methane, carbon dioxide, total non-methane organic compounds (NMOCs), and individual toxic NMOCs based on default composition input or site-specific sampling data.

2.2.1.1. The LandGEM model is based on a first order decomposition rate equation. The estimation tool enables the user to estimate emissions over time using the following input parameters:

- a. Landfill design capacity;
- b. Amount of waste in place or the annual acceptance rate;
- c. Methane generation rate (k), and potential methane generation capacity (L_0);
- d. Concentration of total and speciated NMOCs;
- e. Years the landfill has been accepting waste; and
- f. Whether the landfill has been used for disposal of hazardous waste.

2.2.1.2. Defaults for k and L_0 are suggested for use as input parameters in LandGEM, although more accurate site-specific values can be developed using field test measurements in combination with methodologies specified in USEPA Method 2E. Default input values for both k and L_0 include both conservative values for regulatory compliance evaluation and recommended AP-42 default values. It is also

important to note that effective use of LandGEM and estimates of k and L_0 is also dependent on the knowledge and experience of the modeler. Also refer to USEPA (2005b) and the LandGEM User's Manual for further discussions and recommendations regarding input values. The estimation tool is designed to model and store multiple landfill studies. Within a landfill study, reports and graphs of the estimated emissions can be produced for any particular pollutant, including NMOCs (total and specific), methane, and carbon dioxide.

2.2.1.3. Information on the assumptions used in the LandGEM estimating tool can be found in the accompanying user's manual (USEPA, 2005b) that can also be obtained at the above LandGEM software website.

2.2.1.4. The LandGEM estimating tool has been used by landfill owners and operators to determine if a landfill is subject to the control requirements of the New Source Performance Standard (NSPS) for new MSW landfills (40 CFR 60 Subpart WWW) or the emission guidelines (EG) for existing MSW landfills (40 CFR 60 Subpart CC). The NSPS and EG were initially proposed May 30, 1991 (USEPA, 1991b), and the final rule was promulgated on March 12, 1996 (USEPA, 1996a). LandGEM has also been used to develop estimates for state emission inventories. Given the intended use of the estimating tool for either regulatory compliance or design purposes, there are two sets of default equations for LFG estimates.

2.2.1.5. The following equation should be used if the actual year-to-year solid waste acceptance rate is unknown:

$$M_{\text{NMOC}} = 2kL_a \sum_{i=1}^n M_i (e^{-kt_i}) (C_{\text{NMOC}}) (3.6 \times 10^{-9}),$$

where:

M_{NMOC}	=	total NMOC emission rate from the landfill, megagrams per year over years 1 to n .
k	=	methane generation rate constant, year ⁻¹
L_a	=	methane generation potential, cubic meters per megagram solid waste
M_i	=	mass of solid waste in the i th section, megagrams
t_i	=	age of the i th disposal cell, years
C_{NMOC}	=	concentration of NMOC, parts per million by volume as hexane
3.6×10^{-9}	=	conversion factor

The mass of non-degradable solid waste may be subtracted from the total mass of solid waste in a particular section of the landfill when calculating the value for M .

2.2.1.6. The following equation can be used if the actual year-to-year solid waste acceptance rate is known:

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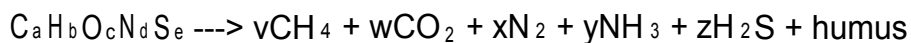
$$M_{\text{NMOC}} = 2L_0 R (e^{-kc} - e^{-kt}) (C_{\text{NMOC}})_{(3.6 \times 10^{-9})}$$

where:

M_{NMOC}	=	mass emission rate of NMOC, megagrams per year
L_0	=	methane generation potential, cubic meters per megagram solid waste
R	=	average annual acceptance rate, megagrams per year
k	=	methane generation rate constant, year
t	=	age of landfill, years
C_{NMOC}	=	concentration of NMOC, parts per million by volume as hexane
c	=	time since closure, years. For active landfill $c = 0$ and $e = 1$
3.6×10^{-9}	=	conversion factor

The value of L_0 is most directly proportional to the waste's cellulose content. The theoretical methane generation rate increases as the cellulose content of the refuse increases. If the landfill conditions are not favorable to methanogenic biological activity (i.e., bacteria that degrade organic matter under highly anaerobic conditions that generates methane), there would be a reduction in the theoretical value of L_0 . This implies that the theoretical (potential) value of methane generation may never be obtained. The obtainable value of L_0 for the refuse (or specific waste components) can be estimated by performing biodegradability tests on the waste under conditions of temperature, moisture, nutrient content, and pH likely to exist in the landfill. Theoretical and obtainable L_0 values have been reported in literature to range from approximately 6 to 270 m^3 of methane generation per metric ton of waste for MSW landfills.

2.2.2. Theoretical Models. The theoretical methane generation capacity (L_0) can be determined by a stoichiometric method that is based on a gross empirical formula representing the chemical composition of the waste. If a waste contains carbon, hydrogen, oxygen, nitrogen and sulfur (represented by $C_a H_b O_c N_d S_e$), its decomposition to LFG is shown as:



However, this type of model is of limited use because it provides an estimate of the total amount of LFG generated, and does not provide information on the rate of generation. It also requires knowledge of the chemical composition of the waste.

2.2.3. Regression Model. The USEPA Air and Energy Engineering Research Laboratory (AEERL) began a research program in 1990, with the goal of improving global landfill methane emission estimates. Part of this program was a field study to gather information that was used to develop an empirical model of methane

emissions. Twenty-one US landfills with LFG recovery systems were included in the study. Site-specific information included average methane recovery rate, landfill size, refuse mass, average age of the refuse, and climate. A correlation analysis showed that refuse mass was positively linearly correlated with landfill depth, volume, area, and well depth. Regression analysis of the methane recovery rate on depth, refuse mass, and volume was significant, but depth was the best predictive variable ($R^2 = 0.53$). Refuse mass was nearly as good ($R^2 = 0.5$). None of the climate variables (precipitation, average temperature, dew point) correlated well with the methane recovery rate. Much of the variability in methane recovery remains unexplained, and is likely due to between-site differences in landfill construction, operation, and refuse composition. A model for global landfill emissions estimation was proposed based on this data.

The following simple model correlating refuse mass to methane recovery with a zero intercept was developed: from these studies:

$$Q_{\text{CH}_4} = 4.52 W$$

where:

$$Q_{\text{CH}_4} = \text{CH}_4 \text{ flow rate (m}^3\text{/min)}$$

$$W = \text{mass of refuse (Mg)}$$

More information on this model can be found in the following publication:
EPA/600/SR-92/037, . Development of an Empirical Model of Methane Emissions
from Landfills .

CHAPTER 5

Operation and Maintenance for Landfill Gas Collection and Treatment Systems

5.1. Introduction. An operation and maintenance (O&M) plan for a landfill gas collection system should be prepared that addresses the following:

- a. Extraction wells;
- b. LFG monitoring probes;
- c. Condensate collection and treatment; and
- d. Flare station.

A site-specific monitoring program should be established that is flexible and performance based. LFG needs to be monitored on a regular basis to enable adjustments to be made to the wells to maximize extraction, prevent migration, and minimize drawing oxygen into the landfill. The procedures need to be regularly evaluated as changing climatic and operational conditions can have an effect on the results obtained. More detailed information on the O&M of LFG collection systems can be found in the reference entitled Landfill Gas Operation and Maintenance Manual of Practice (SWAMA, 1998).

5.2. Extraction Wells.

5.2.1. Composition of Air. Knowledge of the composition of air can be used as an aid in monitoring and adjusting the flows from LFG extraction wells. The following provides a typical composition of air:

Nitrogen (N₂) 78.084%
Oxygen (O₂) 20.947%
Argon (Ar) 0.934%
Carbon dioxide (CO₂) 0.033%
Neon (Ne) 18.2 parts per million (ppm)
Helium (He) 5.2 ppm
Krypton (Kr) 1.1 ppm
Sulfur dioxide (SO₂) 1.0 ppm
Methane (CH₄) 2.0 ppm
Hydrogen (H₂) 0.5 ppm
Nitrous oxide (N₂O) 0.5 ppm
Xenon (Xe) 0.09 ppm
Ozone (O₃) 0.07 ppm
Nitrogen dioxide (NO₂) 0.02 ppm
Iodine (I₂) 0.01 ppm
Carbon monoxide (CO) trace
Ammonia (NH₃) trace

As can be seen above, nitrogen, oxygen, argon, and carbon dioxide are the predominant components (99.998%) of air. The ratio of nitrogen to oxygen is 3.8:1. The ratio of total air to oxygen is 4.8:1. This knowledge can be used to estimate the amount of air intrusion through the cover or to check for leakage into the collection piping.

5.2.2. Monitoring. Balancing a LFG extraction well system is best accomplished by monitoring the well field regularly. Each well should be monitored at least monthly for LFG composition, vacuum, flow, and temperature. The monitoring should be more frequent if the LFG is used as fuel in an energy recovery project. LFG composition measurements may include percentages of methane, carbon dioxide, oxygen, nitrogen, and other constituent gases. If excessive vacuum is applied to a LFG well, ambient air intrusion through the cap or well seals will occur. This phenomenon is called over-pull. Over-pull kills anaerobic bacteria and may increase the chance for an underground fire. The best way to monitor for ambient air intrusion at extraction wells is to check the concentration of nitrogen. Any amount of nitrogen in a well is a sign of ambient air intrusion. Unfortunately, monitoring for nitrogen requires analysis by a gas chromatograph, which is time consuming and expensive. The presence of oxygen is also an indicator of ambient air intrusion; however, oxygen is stripped away as it travels through the refuse by bacteria. Therefore, the concentration of oxygen measured at the wellhead is typically reduced, and is not an exact measure of ambient air intrusion.

5.2.3. Balancing Techniques. Techniques for balancing LFG flow rate for a group of extraction wells include the following:

5.2.3.1. Valve Position. Valve position gives a very rough indication of flow rate assuming similar air permeabilities throughout the landfill (or a correlation of valve position versus flow rate for individual wells has been developed).

5.2.3.2. Wellhead Vacuum. Wellhead vacuum can provide a very rough estimate of radius of influence and flow rate if a pilot study or historical data has provided a correlation between wellhead vacuum and flow/radius of influence.

5.2.3.3. LFG Flow Rate. LFG flow rate is often measured using a fixed device such as a pitot tube, orifice plate, or by some portable measurement device such as an anemometer. The required flow rate at each well and for the system as a whole is generally determined empirically based on LFG composition readings.

5.2.3.4. LFG Composition. Methane, nitrogen, and oxygen are the key parameters measured. Carbon dioxide is often measured in order to indirectly determine nitrogen content, since nitrogen is difficult to measure. Carbon monoxide can be monitored as an indicator of a landfill fire (carbon monoxide is generated if the LFG temperature begins to rise).

5.2.3.5. Summary. The best way to balance a LFG extraction system is by monitoring some or all of the parameters listed above at each individual well, plotting trends over several monitoring events, and reviewing the trends to pick the individual well settings that meets the goals of the extraction system.

5.2.4. Primary Well Field Monitoring. Primary wells are those wells located within the landfill boundaries. The frequency of LFG well field monitoring will vary depending upon field requirements and conditions. Normal monitoring frequency for a complete field monitoring session will vary from once a week to once a month. Well field monitoring should not normally need to be extended beyond once a month for active systems.

5.2.5. Perimeter LFG Migration Control. Perimeter collection wells are located at the edge of the landfill to prevent the off-site migration of LFG. Perimeter systems extract poor quality LFG that is often high in oxygen due to ambient air intrusion at the interface of the landfill and native soil. Operating objectives for the perimeter system are different than the primary wells of a LFG extraction system. The perimeter system provides a final opportunity to capture LFG before it migrates beyond the boundaries of the landfill. The frequency of monitoring is based on the perceived threat to the public from the off-site migration of LFG. Some perimeter migration systems are monitored daily if perimeter LFG monitoring probe readings are above established limits. In other cases, the perimeter system is monitored at the same frequency as the rest of the extraction system. Exceedences of compliance levels for % methane or % lower explosive limit (LEL) at the monitoring probes would likely dictate the need to increase extraction flow rates around the areas of the measured exceedences. Chronic exceedences after increasing extraction flow rates may dictate the need to re-evaluate the well design layout and possibly install additional extraction wells at closer spacings.

5.2.6. Barometric Pressure. The amount of LFG migrating beyond the boundaries of a landfill changes as atmospheric pressure varies, even when the LFG production rate is constant. Methane concentrations and LFG pressure measurements in a monitoring probe may be influenced by changes in barometric pressure. There may be a delay of several hours before equilibrium occurs, and this should be taken into consideration when assessing the collected data.

5.2.7. Leachate Blockage of Extraction Wells. Leachate blockage of LFG extraction wells is occasionally a problem. Leachate in the well is either the result of a high water table or perched liquid that is migrating along a low permeable daily cover soil or a low permeability waste and draining into the well. Once liquid is in the well, it usually drains out slower than it drains in, creating a high leachate level in the well. The following procedure for clearing wells blocked with leachate is suggested (Michels, 1998):

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- a. Discontinue LFG extraction.
- b. Remove the leachate using a temporary down-hole pump or a vacuum truck for wells that are less than 6.096 m (20 feet) deep.
- c. If leachate continues to flow into the well, or it takes more than five days to remove the liquid, then a permanent method of leachate collection is probably required.

Permanent dual LFG/leachate extraction systems typically include the following:

- a. One well casing for LFG extraction and leachate extraction;
- b. LFG extraction wellhead installed at the top of the well casing;
- c. Pneumatic or electric pump installed in the well casing (pneumatic pumps are most common due to the explosive environment); and
- d. Discharge piping headers.

Discharge of the LFG and leachate from the well is typically combined into one header. However, if the LFG and leachate are combined in one header, typically the header is a larger diameter than if it were simply transporting LFG. In addition, condensate dropouts or low points in a combined header system must be enlarged to allow for the added liquids.

5.2.8. Landfill Fires. Spontaneous combustion is the process by which the temperature of a material is increased without drawing heat from an outside source. In landfills, the process occurs when the waste is heated by chemical oxidation via aerobic biological decomposition to the point of ignition. Landfill fires are most easily controlled by limiting ambient air intrusion into the landfill, which will serve to minimize aerobic biological activity that generates heat and elevates the landfill temperature. Atmospheric air is 21 % oxygen and 79% nitrogen. LFG composition typically is measured with a portable LFG analyzer. Instrument readings include percent methane, carbon dioxide, and oxygen. The balance is assumed to be nitrogen. The nitrogen-to-oxygen ratio for atmospheric air is 79/21, which equates to a ratio of 3.76. LFG extraction wells are monitored in order to evaluate system performance. If the oxygen content reaches 3.2% or the nitrogen content is 12% ($3.2 \times 3.76 = 12\%$), ambient air intrusion may be occurring that can create conditions conducive to initiating a landfill fire. If the following is noted during the monitoring of extraction wells, it should be a signal to technicians that conditions are potentially favorable for a landfill fire to occur and increased monitoring or corrective action should be taken:

- a. Oxygen content is increasing and exceeds 3.2 percent by volume.
- b. Nitrogen content is increasing and exceeds 12 percent.
- c. LFG temperature is increasing and exceeds 60 °C (140 °F).

The following parameters are evidence of a fire within the landfill interior:

- a. LFG temperature exceeds 75^o C (167^o F).
- b. Rapid settlement of the cover system.
- c. Carbon monoxide levels are greater than 1,000 ppm.
- d. Combustion residue is present in the LFG piping runs.

Landfill fires can be prevented by:

- a. Decreasing the extraction rate at individual wells, which will in turn decrease ambient air intrusion.
- b. Preventing ambient air intrusion by decreasing the air permeability of the landfill cover.
- c. Increasing the monitoring frequency of the extraction wells and probes.

If an interior landfill fire occurs, fire control may be accomplished through the injection of nitrogen or carbon dioxide into the landfill subsurface to suffocate the fire. Extraction of LFG should also be discontinued to prevent oxygen from being drawn into the landfill (Israel, 2000).

5.2.9. Vertical Profiling. A perimeter LFG extraction well will typically penetrate several geologic layers, with each layer exhibiting different properties. LFG will flow to the well through the path of least resistance (usually through the coarser soils). Vertical profiling within the extraction well can be used to determine what geologic strata methane or other gases are traveling through. The profiling involves using a probe to take continuous LFG samples and measuring its velocity at all levels throughout the length of the well. The results may help provide a better picture of where additional extraction wells should be screened to minimize off-site migration of LFG.

5.2.10. Inspection and Maintenance. Inspection and maintenance should be performed during each sampling event. Each LFG extraction well and monitoring probe should be inspected for damage. Any damage should be noted on the field sampling record and repaired. Piping and associated equipment should be inspected for damage and settlement. Piping runs may develop low spots due to differential settlement. Additional drains or drip legs will need to be installed at these low spots if settlement occurs. Piping needs to be checked for leaks and degradation due to UV exposure. Plastic pipes manufactured without UV resistance may need periodic painting/coating to prevent cracking due to UV degradation.

5.3. LFG Monitoring Probes.

5.3.1. Monitoring Procedures. The reference entitled "Landfill Gas Operation and Maintenance Manual of Practice (SWANA, 1998)" provides excellent

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information on sampling LFG perimeter monitoring probes and interpretation of the collected data. Monitoring probes are typically placed outside the waste mass at the property boundary or the point of regulatory compliance. LFG monitoring probes are typically tested for the following parameters:

5.3.1.1. Probe LFG Pressure. The vacuum/pressure should be recorded by connecting the pressure gauge to the quick connect valve.

5.3.1.2. LFG Concentrations. Purge the probe of two volumes of LFG and then collect vapor samples for measurements using the appropriate instrumentation and record the appropriate concentrations (methane, carbon dioxide, oxygen, nitrogen, hydrogen sulfide, etc.).

5.3.1.3. Groundwater Level. This should be recorded, if applicable.

5.3.1.4. Summary. The technicians name, date, time, ambient temperature, weather conditions, barometric pressure, and probe number are also typically recorded in a field report form during a sampling event. As mentioned previously, LFG is a mixture of various potential vapor phase constituents, including non-methane organic compounds (NMOCs). Periodic monitoring of specific NMOCs may be required to verify no off-site migration.

5.3.2. In-probe Acceptable Levels. In-probe methane levels should be monitored with an infrared LFG analyzer. A methane concentration greater than 5% by volume in a monitoring probe indicates the potential for explosive conditions. Adjustments to the LFG collection system operating procedures should be made if methane levels exceed some specified level (typically 0.5% to 5%) at the perimeter of the landfill or in structures such as vaults, manholes, sumps, or buildings.

5.3.3. Monitoring Frequency. The frequency at which probes are monitored is typically once per week to once per quarter. However, when LFG concentrations exceed acceptable levels, probes should be monitored at an increased frequency (as frequently as once per day). If monitoring probe readings indicate LFG is migrating off-site, consideration should be given to monitoring off-site structures to ensure LFG is not building up in these structures. Examples of structures that should be monitored include basements, crawl spaces, wells, sumps, subsurface vaults, and any other enclosed location where LFG could potentially collect.

5.3.4. Enclosed Structure Monitoring. LFG monitoring must be conducted in any on-site enclosed structures located on top of or adjacent to the landfill. Enclosed areas that contain a potential sparking device (wiring, electrical motor, etc.) should also be monitored routinely. Buildings are typically monitored at least quarterly with a portable LFG instrument at the following locations:

- a. The base of each exterior wall;
- b. Underground utility lines leading into the building; and
- c. Ambient air in each room of the building.

A continuous monitoring device with alarm should be installed in structures that are frequently occupied. Remedial actions (e.g., venting or increasing LFG extraction rate) should be taken if methane concentrations exceed 25% of the LEL (i.e., 1.25% methane by volume).

5.3.5. Surface Emission Monitoring. Surface emission monitoring is typically performed at large municipal solid waste (MSW) landfills that do not have a geosynthetic barrier in the landfill cover. Surface emission monitoring is not commonly performed on USACE projects, because the waste typically found in military landfills does not produce large amounts of LFG. A summary of surface emission testing procedures can be found in the reference entitled "DCOill LFG Operation and Maintenance Manual of Practice (SWANA, 1998)".

5.4. LFG Monitoring Equipment. Common portable measuring instruments for pressure include micromanometers and magnehelic gauges. A combustible gas indicator (CGI) can be used in above-grade monitoring situations when there is sufficient oxygen for the instrument to operate correctly. Below-grade monitoring, as well as situations where oxygen has been displaced by LFG, require use of an infrared gas analyzer. Several specific instruments are common to LFG control systems that should be considered during design. These include:

- a. CGI;
- b. PID;
- c. Infrared gas analyzers;
- d. Colorimetric tubes; and
- e. Field GCs.

Portable field GCs can be used for on-site monitoring. However, this is an expensive option, because laboratory facilities and trained chemists are required for monitoring operations. CGIs operate on two different principles, catalytic oxidation and thermal conductivity. Some CGIs operate by both methods; however, surface emission sampling will focus on the catalytic oxidation method, as the thermal conductivity detection method is used primarily for LFG measurements in migration probes. The catalytic oxidation type of CGI measures the concentration of a combustible gas in air, indicating the results in parts ppm or in % LEL. These readings are often taken in conjunction with oxygen readings. These instruments operate by the detection method of a platinum filament being heated by the combustion of the LFG being sampled. The increase in heat changes the resistance of the filament that results in an imbalance of the resistor circuit called the

"Wheatstone Bridge . This imbalance is measured via the analog or digital scale of the unit. Some CGIs have two scales, one measuring in ppm and the other in % LEL. Limitations to this equipment are as follows:

- a. The reaction is temperature dependent and is, therefore, only as accurate as the incremental difference between calibration and ambient sampling temperatures.
- b. Sensitivity is a function of the physical and chemical properties of the calibration LFG; therefore, methane should be used as the calibration standard.
- c. The unit will not work in oxygen deficient or oxygen enriched atmospheres.
- d. Certain compounds such as lead, halogens, and sulfur compounds can damage the filament. Silicone will destroy the platinum filament. Since LFG contains some halogenated (chlorinated) hydrocarbons, the meter should be calibrated often to methane and serviced annually if it used on a routine basis to monitor methane surface emissions. In addition, if the meter contains an oxygen cell, this cell can be fouled by the carbon dioxide found in LFG, and replacement of the cell may be required frequently.

Advantages are that CGIs are small and portable, self-contained for field use, have an internal battery, are easy to use, and typically are intrinsically safe.

5.4.1. Combustible Gas Indicator/Thermal Conductivity Method .

5.4.1.1. High concentrations of methane (greater than 100% of the LEL or 5% methane by volume) are measured with a CGI using a thermal conductivity (TC) sensor. This type of sensor is often used with a catalytic oxidation sensor in the same instrument. The catalytic sensor is used to detect concentrations less than 100% of the LEL. At higher concentrations, the TC sensor is used to measure up to 100% methane by volume. The TC sensor is composed of two separate filaments heated to the same temperature. Combustible gases enter only the TC side of the filament; the other filament (compensating) maintains a steady heated temperature.

Incoming gases cool the TC filament, and as the filament temperature decreases, the resistance across the Wheatstone Bridge also decreases, resulting in a meter reading. Instruments using a TC sensor do not require oxygen for a valid reading, as burning of the LFG is not involved.

5.4.1.2. Combustible gases vary in their ability to cool the TC filament. Methane absorbs heat well and efficiently cools the filament, and is the calibration gas of choice when using the instrument to measure methane in LFG. However, since LFG is comprised of a combination of different constituents, readings on the meter will vary depending on the concentration of the various constituents in the sample. Gases which cool the filament more effectively than methane (as the calibration gas) will display a higher percent gas reading than is actually present.

5.4.1.3. The converse is also true, that gases which are less effective in cooling the filament will display a lower percent gas reading than is actually present.

It is important to realize that certain gases can cool the filament and not be combustible. Carbon dioxide absorbs heat readily and can produce a false positive reading. Meter sensitivity to carbon dioxide varies from manufacturer to manufacturer, so one should be very familiar with the technical information supplied with the equipment. With some meters, calibration with a methane/carbon dioxide mixture can help alleviate the interference of carbon dioxide.

5.4.1.4. There must be sufficient oxygen present in the atmosphere being analyzed for a CGI to work correctly. Therefore, the CGI is a poor instrument selection for monitoring explosive conditions (methane concentrations) directly, since oxygen levels can be very low.

5.4.2. Flame Ionization Detector (FID)/Organic Vapor Analyzer (OVA)

5.4.2.1. FIDs measure many organic gases and vapors, and unlike PIDs will detect methane. Some FIDs are commonly referred to as OVAs. FIDs operate by a sample being ionized in a detection chamber by a hydrogen flame. A current is produced in proportion to the number of carbon atoms present. There are two modes of operation, the survey mode and the GC mode. For methane surface emissions, the survey mode is used if both are available on the instrument. Since the sensitivity of the instrument depends on the compound, methane should be used as the calibration standard. These instruments are less rugged in the field than the CGIs and require hydrogen gas cylinders for use.

5.4.2.2. The advantages to the FIDs are fast response in the survey mode, wide sensitivity (1 to 100,000 ppm), and some models offer a telescopic probe with cup intake that minimizes operator exposure to LFG and minimizes the effects of windy conditions at the site. The "cup" probe design can also serve to reduce the near surface dilution effects of the wind by providing a small sampling chamber when the probe is held normal to the surface. The zero on the FID should be checked daily, since it often drifts upward during use.

5.4.3. Infra-Red (IR) Analyzer

5.4.3.1. Infrared is a range of frequencies within the electromagnetic spectrum. The infrared frequencies act to set the molecules of chemicals into vibration. Chemicals have a vibration energy that is specific to that chemical. When the gas interacts with IR radiation, it absorbs a portion of the IR energy. The absorption spectrum for that gas is the pattern of vibrations from the atoms/functional groups, along with the overall molecular configuration. Specific gases will demonstrate optimal absorption within a small IR range. Since absorption ranges have been classified for different gases, it is possible to filter out all but a

small part of the spectrum and measure the vapor constituent known to be present. The advantage of IR analyzers is that the high carbon dioxide levels found in landfills will not affect methane readings.

5.4.3.2. Most IR analyzers are single beam spectrophotometers. Portable IR meters available for the field are capable of measuring up to 100% by volume methane and carbon dioxide. The concentrations of these gases are detected by infrared absorption. Oxygen concentration is measured by an electrochemical cell. These meters are designed to measure large concentrations of methane and carbon dioxide and are not sensitive at concentrations less than 0.5%. A field calibration gas should be used to verify the accuracy of the monitoring results. A combination gas of 15% methane and 15% carbon dioxide is a common mixture when using the equipment to test migration probes. Higher concentrations of calibration gases should be used if monitoring levels in LFG extraction wells.

5.4.4. Colorimetric Indicator Tubes. If necessary for regulatory or health and safety purposes, specific NMOCs can be measured in the field using colorimetric tubes that are calibrated for specific chemicals or family of chemicals. Alternatively, samples can be collected for laboratory analysis using Summa canisters for off-site laboratory analysis of specific organic constituents. Colorimetric tubes are typically used as a screening tool only for measuring ambient air concentrations for health and safety or other purposes, since the accuracy of their concentration readings can have an error rate as great as 25% and are subject to various interferences. Colorimetric tubes are capable of measuring air concentrations within a specified range, so some knowledge of the anticipated constituent concentration is needed to select an appropriate tube for use. Previous measurements using field screening instrumentation (e.g., PID) can sometimes be used to estimate the expected concentration. If unknown, then colorimetric tubes representing different concentration ranges should be used for the initial measurements.

5.4.4.1. Various manufacturers exist for colorimetric tubes that offer different chemical and concentration range capabilities. Each manufacturer has its own hand sampling pump that must be used with its brand of colorimetric tubes. It is beneficial to review each manufacturer's line of colorimetric tubes to identify the one(s) that best fit the measurement needs (i.e., chemical specificity and concentration range). Sampling pumps that match the selected colorimetric tube can either be rented or purchased, depending on the frequency of need. The instructions for each colorimetric tube should be carefully reviewed before use to identify the proper number of sample pulls, calibration of tube reading to actual concentrations, other chemicals that can interfere with or skew the measurements, and other use requirements.

5.4.4.2. To perform a measurement using colorimetric tubes, an LFG sample from the piping line must first be collected (if consistent measurements cannot be

obtained directly from the line). The easiest method for collecting a LFG sample is to use a portable vacuum pump to draw a LFG sample from the piping line into a Tedlar bag. The vacuum capacity of the sample pump must be greater than the line vacuum to pull a sample that is not diluted by ambient air (all connections must also be tightly sealed). A short tubing connection can then be used between the Tedlar bag and colorimetric tube to make a tight seal that will allow the hand drawn sample to be drawn through the tube. The change in indicator color allows the measurement to be read off the tube and then converted to the actual concentration measurement in accordance with the instructions.

5.5. Condensate Collection and Treatment. Disposal of LFG condensate is an issue common to most landfill sites in humid climates. Methods of disposal for LFG condensate include the following.

5.5.1. Treatment. LFG condensate can be collected from the various condensate collection points and treated prior to release. When a liner system is present, condensate is commonly combined with landfill leachate and disposed of in the same manner as the leachate.

5.5.2. Injection/Recirculation. Federal solid waste regulations allow leachate and condensate recirculation if the landfill has a composite liner system. Recirculation employs the absorptive properties of the MSW to hold the condensate within the material. However, once the MSW reaches field capacity or decomposes, condensate recirculation in that portion of the site is no longer effective and will short-circuit directly into the leachate collection system. Condensate injection/recirculation is being practiced at numerous sites, and is accomplished primarily through drainage into the collection well field at moisture traps.

5.5.3. Aspiration into the LFG Flare. This method of condensate disposal consists of spraying it directly into a LFG enclosed flare. This technology can typically destroy up to one gallon per minute of condensate. The popularity of this method of disposal is increasing. Aspiration of condensate into LFG flares has been accomplished on several sites and appears to be an efficient and effective method of condensate disposal, provided the condensate is non-hazardous. Flare destruction efficiency is dependent on the following: flare temperature, flare residence time, and turbulence. Tests must be conducted to ensure that condensate aspiration will not cause an unsatisfactory drop in operating temperature of the flare. Analysis of LFG condensate quality, pre-aspiration flare emissions quality, and emission quality during aspiration are typically required. Condensate is transferred from a liquid state to vapor upon aspiration into the flare. This requires approximately 12,000 BTUs of energy per gallon of condensate. With the aspiration of condensate into the flare unit, draft velocities are created during condensate evaporation that could significantly change the retention time on which the original flare design was based. Recent applications of condensate aspiration, however, have not caused a decrease

in destruction efficiencies. Only enclosed flame flares provide adequate residence time for condensate aspiration. Collected condensate is typically collected either for on-site treatment or off-site disposal at a POTW or commercial disposal facility.

5.5.4. Summary.

5.5.4.1. Data that have been published shows that the aqueous phase concentrations of LFG condensate are generally below the Resource Conservation and Recovery Act (RCRA) Toxic Compound Leachate Procedure (TCLP) criteria, which should allow for disposal as a non-hazardous waste. If a non-aqueous phase liquid is present in the condensate, this fraction has been found to typically exceed the RCRA characteristic ignitability criteria, which would require disposal as a hazardous waste. Landfills that have been operating principally as MSW landfills are rarely found to have a significant non-aqueous phase fraction in its condensate.

5.5.4.2. In preparing the proper management plan for condensate, it should first be determined if the condensate contains two phases. If the condensate does have a non-aqueous phase, management plans should include a phase-separation process to separate the non-aqueous phase liquids from the aqueous phase fraction.

5.6. Flare Station. Maintenance and inspection of a blower/flare station is commonly performed on a weekly basis. Activities include LFG flow rate alteration, mechanical repair, lubrication, pilot/auxiliary fuel refill, and equipment cleaning. The total blower LFG flow rate at the station may need to be adjusted due to changes in the flow rate or to eliminate off-site migration. Partially opening or closing the valve on the blower inlet side usually accomplishes flow rate adjustments. The following paragraphs describe additional monitoring requirements associated with various components of a blower/flare system.

5.6.1. Blower.

5.6.1.1. Monitoring Requirements. Inspection of this unit should include recording the flow rate and pressure of the system for comparison against the manufacturer's blower curve. The pressure drop across the blower should also be monitored using permanent gauges or portable magnehelic gages at entrance and exit ports on the blower.

5.6.1.2. Frequency. Monthly inspections should be made, unless recommended otherwise by the manufacturer, to ensure that operating parameters are within expected ranges. After the first year and every second year thereafter (at a minimum), comprehensive inspections by a representative of the manufacturer should be made to determine if parts are wearing at an excessive rate. Should the

equipment warranties recommend more frequent inspection, this frequency should be upgraded to the recommended levels.

5.6.2. Flame Arrestor.

5.6.2.1. Monitoring Requirements. Monitoring of the flame arrestor consists of measuring the head loss across the flame arrestor to ensure that operating head losses are not significantly above or below the losses expected for the unit. In general, flame arrestors require little maintenance (cleaning) and are rarely replaced in operating systems.

5.6.2.2. Frequency. Inspection of the flame arrestor can be infrequent since it does not have any moving parts. Monthly inspections conducted with several other portions of the LFG collection and flaring system will be adequate.

5.6.3. Flare.

5.6.3.1. Monitoring Requirements. The flare unit should be capable of operating at >98 percent destruction requirement efficiency (DRE) for methane. In addition to DRE monitoring, the flare inlet should be inspected for:

- a. LFG flow rates;
- b. LFG supply pressure;
- c. Minimum operating temperatures; and
- d. Influent LFG parameters (including methane, carbon dioxide, oxygen, and regulated NMOCs).

5.6.3.1.1. ODCNDF1DIJI's recommendations for minimum and maximum values for these parameters should be determined for the specific flare unit. Manufacturers typically specify a minimum supply pressure for a given flow rate. Inspection should include referencing operating parameters of flow rate and pressure drop against the design curve established for the flare. Inspection should verify that a sufficient delivery pressure is being supplied for the observed flow rate.

5.6.3.1.2. The temperature of the flare unit should be monitored to ensure that this parameter is being maintained. The methane content and flow rate of the influent LFG should be inspected as described below. Excessive operating temperatures should not occur, since the flare unit should be designed with automatically adjusting air intake louvers. However, if excessive temperatures (i.e., > 980 C [1,800 F]) are observed, controls for these louvers should be inspected.

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5.6.3.1.3. LFG parameters. Methane, oxygen, and carbon dioxide levels should be recorded to verify that the operating concentrations are within acceptable ranges for the flare.

5.6.3.2. Frequency. Monthly monitoring is recommended unless suggested otherwise by the manufacturer. Certain operating parameters, including LFG flow rates, LFG supply pressure, minimum operating temperature, and inflow LFG parameters should be measured and recorded more regularly.

5.7. Maintenance Requirements. The O&M of a LFG management system should be structured to maintain the operation goals (e.g., 98% reduction of NMOCs). An O&M program can be divided into the following categories:

- a. Routine O&M;
- b. Non-routine maintenance; and
- c. Emergency services.

5.7.1. Routine Maintenance. A routine maintenance program includes periodic maintenance and preventive maintenance. During routine maintenance, testing and checking of the following components should be performed:

- a. Extraction wells;
- b. Collection header;
- c. Monitoring wells and probes;
- d. Oil change for blower;
- e. Flame arrestor cleaning;
- f. Condensate handling;
- g. LFG detection system;
- h. Pilot/auxiliary fuel; and
- i. Periodic leak testing or screening using field instrumentation (e.g., FID) of major valves and equipment for LFG losses.

5.7.1.1. Pilot/auxiliary fuel refilling and equipment cleaning should be performed at least weekly. In particular, the combustion mechanism requires regular cleaning to assure that the gases are burned completely. Air and oil filters should be checked and changed routinely after a specific number of hours as recommended by the manufacturer. This will prevent more costly and time-consuming repairs down the line. Preventive maintenance includes blower bearing lubrication and flame sensor cleaning.

5.7.1.2. Regular oil changes should also be performed on the blower (positive displacement blowers), compressor, gearbox, and combustion systems. This will

help ensure that the process operates smoothly and efficiently, and it also reduces the chance of costly downtime associated with more significant repairs.

5.7.2. Non-Routine Maintenance. Non-routine maintenance activities consist of corrective repair or maintenance of work identified during the routine inspection. These may include:

- a. Repair or replacement of failing components; and
- b. Testing and adjusting the collection system if air intrusion is observed.

5.7.3. Emergency Services. Emergency services are those requiring immediate response to prevent human injury, property damage, or regulatory non-compliance. These activities may include:

- a. Responding to system failure or shut down; and
- b. Executing contingency plans, if required.

5.7.4. Equipment Calibration. The instruments used for measurements are customarily correct to within a certain percentage of the “true” value. This accuracy is generally expressed by the instrument’s manufacturer as the “inherent error of the device”. Instrument calibration does not lead to elimination of error; it does allow the equipment to provide representative numbers for the subject measurement to the best of the machinery’s ability. Routine calibration and servicing are necessary to assure the quality of measurements made using these instruments. Permanently installed equipment used for measurements should be calibrated according to the manufacturer’s recommendations and the quality assurance program.

5.7.5. System Adjustments Based on Monitoring Data. Landfill operators have to adopt a variety of monitoring parameters, techniques, and frequencies to balance the vacuum system to optimize the volume of collected LFG and/or contain the LFG in all parts of the landfill. For example, the LFG flow rate at the station may need to be reduced due to landfill aging and corresponding reductions in LFG generation. Throttling the control valve on the blower inlet side or at individual extraction wells usually accomplishes the necessary adjustments to reduce total system LFG extraction rate.

5.8. Record-Keeping and Contingency Plan. All inspection and maintenance records must be saved and kept at a location that is easily accessible. If measured methane levels at the compliance points are in excess of regulatory levels or the flare emissions are out of compliance, then the facility must report the results to the appropriate regulatory agency and take steps to correct the situation. An increased frequency of monitoring should then be made until the situation is corrected.

CHAPTER 6 Regulatory Requirements

6.1. Introduction.

6.1.1. This chapter discusses environmental regulations as they pertain to landfill gas (LFG) emissions. Regulations addressed in this section include Resource Conservation and Recovery Act (RCRA) solid and hazardous waste management requirements, Clean Air Act (CAA) requirements, and Clean Water Act (CWA) requirements associated with LFG generation and emissions. Many of the regulations discussed below apply to currently operating or recently closed landfills, and may not be appropriate for landfills that stopped receiving wastes prior to 1987. It is important that personnel know the federal and state regulatory framework under which the LFG control is being done (e.g., general non-hazardous solid waste/refuse disposal, CERCLA remediation, RCRA Corrective Action, etc.) in order to determine which, if any, of the following requirements must be met.

6.1.2. The discussion of applicable regulations and legal requirements in this chapter is only meant to make the reader aware of some of the many requirements that may potentially apply to LFG emissions and disposal of condensate. This chapter is not intended to stand in place of any applicable law, regulation, or standard, and may not reflect the current standards embodied in law and regulation. Statutes and regulations are the controlling rule of law and should always be consulted to determine how they apply to a particular set of circumstances to assure compliance before action is taken. USACE will comply with all applicable laws and regulations. The PM district will provide general legal services in support of FUDS and FUSRAP. For FUDS and FUSRAP projects, the determination of the laws and regulations governing environmental aspects for any specific project will be made in consultation with the Office of Counsel. In the event of any dispute with a regulator over the governing laws on a FUDS or FUSRAP project, the District providing general legal services will represent the agency in negotiations or adversary proceedings. For other work performed by USACE under a different program or authority (i.e., BRAC, IRP, Work for Others), the appropriate legal representative of the sponsoring agency will be the lead counsel for all legal matters, although the USACE Office of Counsel will be available for consultation.

6.2. Summary of Applicable Regulations. Regulations affecting LFG management are addressed under various legislation, which may include the following:

- a. RCRA, which regulates solid and hazardous waste management, such as the landfill itself;
- b. CAA, which regulates air emissions; and

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c. CWA, which regulates discharges of water such as LFG condensate and storm water runoff. A brief summary of potential federal regulations applicable to LFG management follows.

6.3. Resource Conservation and Recovery Act Regulations. Under RCRA, if LFG is emitted or condensate is treated and/or disposed, RCRA requirements may have to be met. Primary RCRA requirements pertaining to LFG emission and condensate disposal are found in the following regulations:

40 CFR Part 258 [regulations for LFG emissions from MSW (non-hazardous) landfills];

40 CFR Parts 260-261 [regulations for characterization and disposal of condensate as a hazardous waste];

40 CFR Part 262 [regulations pertaining to hazardous waste generator requirements]; and

40 CFR Part 268 [regulations for hazardous waste land disposal restrictions].

6.3.1. Response actions taken under CERCLA (IRP, FUDS, BRAC or Superfund) are not required to obtain RCRA permits for on-site treatment or storage. However, compliance with substantive requirements, such as physical storage requirements and containers, will most likely have to be met.

6.4. Clean Air Act Regulations. Since passage of the Federal CAA in 1970, many rules and regulations have been adopted that could potentially affect LFG operations. The applicability of these rules and regulations are governed by specific factors, such as the implementation schedule of the rule, size of the facility, the equipment and type of operations conducted at the site, and the emissions from these operations. For example, to establish whether the CAA New Source Performance Standards (NSPS) or Engineering Guideline (EG) controls are applicable to a specific landfill, the non-methane organic compound (NMOC) maximum annual emissions must be greater than or equal to 50 million grams per year (Mg/yr). If the maximum annual NMOC emission rate is greater than or equal to 50 Mg/yr and the design capacity and applicability cut-off dates are triggered, the landfill may be subject to the NSPS or EG. Personnel need to be familiar with the specific requirements of each regulation prior to deciding whether or not the requirements apply to their project. Potentially applicable CAA regulations include:

40 CFR Part 60 [NSPS];

40 CFR Part 63 [National Emission Standards for Hazardous Air Pollutants (NESHAPs)];

40 CFR Part 70 [Title V operating permits]; and state and local air quality regulations.

6.4.1. USEPA designed the Title V operating permit program as a central mechanism to regulate emissions, monitoring data needs, compliance schedules, fee payments, and other conditions associated with the issuance, compliance, and enforcement of operating permits. Personnel involved in designing LFG control systems should ensure that the customer is made aware of calculated LFG emissions and what control devices will be used to control them. This information is important to the customer who is ultimately responsible for determining the need to obtain a Title V operating permit or to revise an existing permit. Any questions regarding the need to obtain an operating permit for the LFG control system should be discussed with the customer and the project team.

6.4.2. Response actions taken under CERCLA (IRP, FUDS, BRAC or Superfund) are not required to obtain CAA permits for on-site emissions and treatment systems. However, compliance with substantive requirements, such as the attainment of emission criteria and use and design of specific treatment technologies, will most likely have to be met.

6.5. Clean Water Act Regulations. Under the CWA, if LFG condensate is disposed of by treatment and effluent discharged to regulated “waters of the United States”, a National Pollution Discharge Elimination System (NPDES) discharge permits is required. Separate NPDES regulatory and permit requirements may also cover storm water run-off associated with a landfill. An NPDES permit would most likely include effluent concentrations/limits that must be met based on a state's water quality standards for the receiving surface water body into which the effluent is being discharged. Effluent analyses that may be required as part of an NPDES permit could include:

- a. Biochemical oxygen demand (BOD);
- b. Chemical oxygen demand (COD);
- c. Total organic carbon (TOC);
- d. Total suspended solids (TSS);
- e. Ammonia (as nitrogen);
- f. Temperature;
- g. pH; and
- h. Flow.

6.5.1. Response actions taken under CERCLA (IRP, FUDS, BRAC, or Superfund) are not required to obtain NPDES discharge permits. However, substantive requirements, such as numerical discharge limits, may still have to be established and met at these sites, especially when condensate is discharged via a point source to regulated “waters of the United States”.

6.5.2. Other analyses may be required if other pollutants are expected to be present. Permittees may also be required to test their discharge for toxicity. If the condensate is disposed of by indirect discharge through a publicly owned treatment works (POTW), sewer effluent conditions would be imposed by the local jurisdiction as regulated by local ordinances or federal requirements.

6.6. State and Local Requirements. Many states and local authorities have also adopted rules that impact LFG emissions and disposal of condensate. The CAA, RCRA, and CWA all contain provisions that generally subject federal facilities to state and local requirements, both substantive and procedural, controlling the same subject matter as the respective federal laws. The appropriate Office of Counsel must be coordinated with to determine whether state and local requirements are applicable to federal activities for a given circumstance. States can, and frequently do, have regulations that are more stringent than the federal requirements. It is crucial that personnel know the specific requirements of the state in which the project is located, and whether those requirements apply in a specific circumstance, in order to ensure compliance with applicable regulations.