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LANDFILL OFF-GAS COLLECTION AND TREATMENT SYSTEMS

ENGINEER MANUAL

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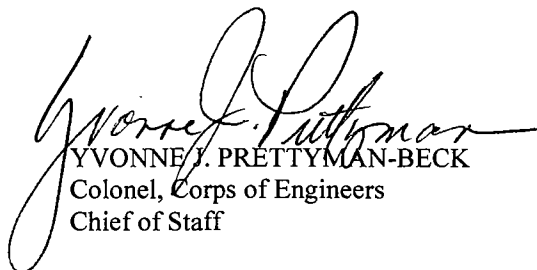
Engineering and Design
LANDFILL OFF-GAS COLLECTION AND TREATMENT SYSTEMS

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

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

3. **Distribution Statement.** Approved for public release and unlimited distribution.

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

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

FOR THE COMMANDER:

2 Appendices
(See Table of Contents)

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Chapter 4. Design of Landfill Off-Gas Treatment Systems

CHAPTER 1
Introduction

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

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

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

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

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

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

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

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

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

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

Table 1-1.
Pressure Conversion Factors.

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

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

$$P_A = H_A \times X_A$$

where

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

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

1.4.3. *Biological Decomposition.* Sanitary landfills produce large quantities of gas, with the major components being methane (CH_4) and carbon dioxide (CO_2). LFG generation occurs as a

result of two conditions, aerobic and anaerobic decomposition and can be divided into three distinct phases, however, it is important to understand that there will be both aerobic and anaerobic degradation occurring at the same time.

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

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

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

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

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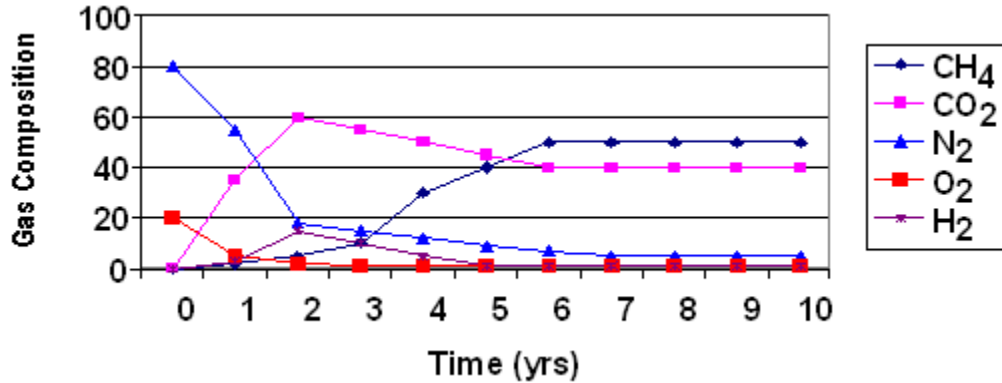
Figure 1.1. Landfill Gas Composition.

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

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

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

1.5.1. *Waste Composition.* The primary nutrients (macronutrients) required for bacterial growth in a landfill are carbon, hydrogen, oxygen, nitrogen, and phosphorus. Small amounts of other elements (micronutrients) such as sodium, potassium, sulfur, calcium, and magnesium are also required for bacterial growth. The availability of macronutrients in the landfill mass has an affect on both the volume of leachate generated from microbial processes and the composition of the generated gases. Landfills that accept municipal wastes generally have an adequate nutrient supply

for most microbial processes to proceed. Specialized landfills such as those at military installations that handle hazardous materials or munitions wastes only, may not have sufficient nutrients in the waste to sustain a large microbial population. The primary sources of macronutrients are yard wastes and food wastes. Micronutrient requirements are very small and can usually be met by the trace amounts found in wastes and/or leached from cover soils.

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

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

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

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

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

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

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

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

Table 1-2.
Density of the Waste.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Table 1-3.
Landfill Gas Characteristics.

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

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

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

Table 1-4.
Typical Values for Gas Density and Viscosity at 0^oC and Atmospheric Pressure

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

1.8.2. *Heat Value Content.* During the methanogenic stage, LFG can be expected to have a heating value of 500 Btu/ft^3 under good conditions. This value is about half that of natural gas. The

actual heating value of the gas from a landfill is a function of the type age of the waste, the type of landfill cover, and many other factors that have been discussed previously in this section.

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

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

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

1.9. **LFG Condensate**.

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

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

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

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

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

Table 1-5.
Organic Contaminants.

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

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:

- Size and depth of the landfill.
- Nature of the waste and the potential for producing methane and other gases.
- Age of the waste.
- Type of cover and liner present.
- Existing gas collection and monitoring systems.
- Hydrogeologic conditions surrounding the landfill.
- 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 needs to be gathered in order to estimate the amount of gas being generated and whether or not the gas is migrating off-site. The following paragraphs describe methods of site characterization, quantifying landfill gas production, and the potential for off-site migration.

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, soils gas surveys and pump tests can be used to better quantify the amount and types of landfill gas being produced. Soil gas surveys and pump tests are described later in this section.

2.1.3. *Hydrogeologic Conditions.* The migration of landfill gas 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 gas vapors as readily. These zones also tend to retain more moisture due to capillary forces and this poses an additional barrier to vapor flow. High permeability layers in contact with landfills are capable of transmitting gases over large distances, especially when they are overlain by a continuous layer of low permeability material.

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 and EM 1110-1-4000 Monitor Well Design, Installation, and Documentation at Hazardous and/or Toxic Waste Sites provides general information on performing field investigations

and well installation. The Table 2-1 lists important parameters that should be determined when investigating the off-site migration of landfill gas.

Table 2-1.
Important Parameters that Affect Off-Site Migration of Landfill Gas.

Parameter	Collection Method	Reference
Stratigraphy	Soil borings	EM 1110-1-1804 ASTM D 2487 ASTM D 2488
Depth to ground water	Monitoring wells	EM 1110-1-4000
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
Soil gas concentration	Gas monitoring probes	EM 1110-1-4001
Soil gas surveys	Gas monitoring probes	EM 1110-1-4001

2.1.4. *Ambient Air Quality.* Ambient air quality monitoring may be necessary to help determine the need for a landfill gas 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.). Ambient conditions including temperature, barometric pressure and precipitation events should be recorded. Gaseous parameters analyzed may include CH_4, H_2S, and NMOCs. Additional information regarding modeling and monitoring air quality for landfill emission sources can be found in EP 1110-1-21, Air Pathway Analysis for the Design of HTRW Remedial Action Projects.

2.1.5. *Gas Monitoring Probes.* Gas monitoring probes can be used during the investigation phase or for long-term monitoring to determine if gas is migrating off-site through the subsurface. Gas probes should be installed in the more permeable strata, between the landfill unit and either the property boundary or structures where gas migration may pose a problem. Multiple or nested probes are useful in defining the vertical configuration of the migration pathway (EPA, 1993). Probe location and spacing is dependent of geologic conditions, water table conditions, and adjacent property use. Gas monitoring probe design and construction requirements are discussed in later sections of this document.

2.1.6. *Monitoring Gases 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 landfill gas during the investigative phase.

2.1.7. *Soil Gas Surveys.* Soil gas surveys can provide information about the production and migration of landfill gas. They are also much less expensive and require considerably less field time

than alternative sampling methods such as the installation of 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:

- Characterization of landfill gas composition as an indicator of the nature of the waste or to determine the health risk posed by the landfill gas
- Design of landfill gas collection and treatment systems
- Identification of landfill gas migration.
- Assess the soil vapor intrusion pathway at landfills where soil gasses may be carrying VOC's into buildings.

2.1.7.1. *Sampling Depths.* Soil gas 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. Landfill gas samples for characterization of gas composition and design of landfill gas collection and treatment systems should be taken at least 3 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 landfill gas 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 landfill gas 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 landfill gas migration, the spacing of sample collection points may be dictated by regulation, but should consider the scale of heterogeneity in potential gas 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. 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 off-gas treatment system design, for determination of risk posed by the landfill gas or for quantifying gas migration to receptors. These

samples represent a snapshot of the soil gas concentrations and are, therefore, susceptible to variations due to changes in barometric pressure, gas 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 (e.g., cone penetrometer) or a drill rig. Drilling into a landfill requires additional safety precautions and in accordance with EM 385-1-1, a hazard task analysis for the work should be completed prior to drilling. 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. Typically, decontaminated steel pipe/probes are used for temporary sampling probes, although steel 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 atmospheric air entry are critical. Refer to EM 1110-1-4001, 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 gas. Typically, 3-5 times the well volume is purged. Monitoring of vapor concentrations as purging progresses can indicate the ideal amount of purging, however, 3 volumes is typically a minimum. 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 analysis. 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 1110-1-4000, 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 gas 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, gas 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 soil gases 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 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 landfill gas 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 landfill gas production rate is calculated. Gas 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 gas 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, EPA Method 2E - Determination of Landfill Gas Production Flow Rate can be used to calculate the flow rate of nonmethane organic compounds (NMOC) 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 pressure differentials from the wells are measured and the landfill gas production flow rate is calculated from this data. EPA Method 2E can be found 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. EM 200-1-3 "Requirements for the Preparation of Sampling and Plans" provides guidance on selecting the most appropriate type of sampling approach, i.e., the number of samples that should be collected from each medium, and the laboratory analyses that should be performed to achieve the objectives of the sampling program with the desired level of confidence.

2.1.9.1. *Field Analyses.* Field analyses can be used to get an initial estimate of conditions at the site. Field analyses is 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.

Infrared instruments are typically used to monitor landfill gasses (methane and carbon dioxide) below grade and explosimeters are typically used to monitor potential explosive atmospheres above grade. A PID or indicator tubes may also be used to monitor toxic air contaminants at above grade locations. The use of field portable GCs and GC/MSs is acceptable if there is a need to identify specific chemical contaminants, 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. The methods typically specified have quality control requirements, and the use of a quality assurance lab provides a measure of the adequacy of the primary 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 volatile organic compounds (VOCs) in ambient air. The method was originally based on collection of whole air samples in summa passivated stainless steel canisters, but has now been generalized to other specially prepared canisters.

    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. Gas 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 gas treatment systems, the raw concentrations of soil gas are typically averaged over the area of the collection system.

2.2. **Estimation of LFG Emissions.** LFG emissions are site-specific and are a function of both controllable and uncontrollable factors. It is, therefore, difficult to accurately predict the rate of LFG emission from a landfill. A summary table of reported methane generation rates is provided in Table 3-1. One approach to predicting gas generation from a municipal solid waste 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 is one of these models and was developed by the US Environmental Protection Agency to estimate landfill gas emissions and to determine regulatory applicability to CAA requirements. There are other LFG emission models in use by industry that also work very well. The Clean Air Act regulations allow states the opportunity to use the results from models other than LandGEM. However, most of these models are proprietary and are 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, it makes estimating landfill emissions very difficult.

2.2.1. *LandGEM*. LandGEM provides an automated estimation tool for quantifying air emissions from municipal solid waste (MSW) landfills. The LandGEM software can be obtained from the following web site: http://www.epa.gov/ttn/atw/.

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

- Landfill design capacity
- Amount of waste in place or the annual acceptance rate.
- Methane generation rate (k), and potential methane generation capacity (L_o).
- Concentration of total and speciated nonmethane organic compounds (NMOCs).
- Years the landfill has been accepting waste.
- Whether the landfill has been used for disposal of hazardous waste.

2.2.1.2. Defaults for k and Lo are suggested although site-specific values can be developed through field test measurements and then used in the software to develop more accurate estimates. The program 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 speciated), methane, and carbon dioxide.

2.2.1.3. Information on the assumptions used in the model can be found in the background information document (EPA, 1991a) written to support the Standards of Performance for New Stationary Sources (NARA, 1997a) and Emission Guidelines for Control of Existing Sources (NARA, 1997b) and in the public docket (McGuinn, 1988a; McGuinn, 1988b; Pelt, 1993).

2.2.1.4. The software is being 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 (EPA, 1991b), and the final rule was promulgated on March 12, 1996 (EPA, 1996a). LandGEM is also being used to develop estimates for State emission inventories. Given the intended use of the software, there are two sets of defaults.

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

$$M_{\text{NMOC}} = 2kL_o \sum_{i=1}^{n} M_i (e^{-kti})(C_{\text{NMOC}})(3.6\times10^{-9})$$

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_o =   methane generation potential, cubic meters per megagram solid waste

M_i =   mass of solid waste in the ith section, megagrams

t_i =   age of the ith section, years

C_{NMOC} =   concentration of NMOC, parts per million by volume as hexane

3.6×10^{-9} =   conversion factor

The mass of nondegradable 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_i.

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

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

where:

M_{NMOC} =   mass emission rate of NMOC, megagrams per year

L_o =   methane generation potential, cubic meters per megagram solid waste

R =   average annual acceptance rate, megagrams per year

k =   methane generation rate constant, $year^{-1}$

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 $e^{-kc} = 1$

3.6×10^{-9} =   conversion factor

The value of L_0 is most directly proportional to the waste's cellulose content. The theoretical CH_4 generation rate increases as the cellulose content of the refuse increases. If the landfill conditions are not favorable to methanogenic activity, there would be a reduction in the theoretical value of L_0. This implies that the theoretical (potential) value of CH_4 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 CH_4 per metric ton of waste for municipal land-fills.

    2.2.2. *Theoretical Models.* The theoretical CH_4 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 $C_aH_bO_cN_dS_e$), its decomposition to gas is shown as:

$C_aH_bO_cN_dS_e \text{ ---> } vCH_4 + wCO_2 + xN_2 + yNH_3 + zH_2S + \text{humus}$
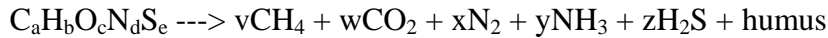
However, this type of model is of limited use because it provides an estimate of the total amount of gas generated and does not provide information on the rate of generation. It also requires knowledge of the chemical composition of the waste.

2.2.3. *Regression Model.* The EPA 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 gas 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 ($R^2 = .5$). 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. A simple model correlating refuse mass to methane recovery with a zero intercept was developed:

$Q_{CH4} = 4.52\ W$

where:

Q_{CH4} = CH_4 flow rate (m^3/min)
W = 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 3
Design of Landfill Off-Gas Collection Systems

3.1. **General**. Gas control systems consist of collection, conveyance, and treatment components and are designed to be either passive or active. A passive system allows the landfill gas to exit the collection system without mechanical assistance, whereas an active system uses mechanical assistance, such as blowers, to extract gases. Depending on the potential impacts of the landfill gas and local regulatory criteria, gases are either dispersed into the atmosphere or collected and treated. Design of collection systems and conveyance piping are described in this section.

3.2. **Methods of Gas Collection**. LFG is generally collected using gas collection wells, blankets, or trenches. The following sections describe each of these types of systems.

3.2.1. *Wells.* Well systems consist of a series of vertical gas extraction wells (perforated or slotted collection pipes) that penetrate to near the bottom of the refuse or to near the depth of saturated waste. Well systems are often recommended for landfills or portions of landfills that exceed 12 m (40 ft) in depth. The design of a well system requires an estimate of the rate of gas production and the radius of influence of the wells. A well system, either active or passive, is useful for layered landfills where vertical gas migration is impeded. Because of the variability of landfill refuse, design procedures are difficult to apply to gas collection systems. Gas collection wells are commonly spaced at a frequency of one per acre and are constructed using an auger type drill rig.

3.2.1.1. *Active Gas Vent Well Design.* The method of construction and components of active LFG extraction wells are similar to those of standard ground water monitoring or extraction wells (i.e., riser, screen, gravel pack).

3.2.1.1.1. *Borehole.* The borehole diameter for an active gas collection well will typically range from 0.3 to 1 m (1 to 3 ft). The well boring will typically extend from the landfill surface to near the bottom of the waste. If the landfill contains a liner system beneath the waste, the well should be terminated a safe distance above the liner system to prevent damage.

3.2.1.1.2. *Casing.* A minimum 100 mm (4-inch) diameter HDPE or PVC casing is placed in the boring. The casing diameter should be based on pneumatic analysis of the system and anticipated LFG flow rates. In cases where landfill temperatures are high, other screen/casing materials such as steel and fiberglass should be considered. The operating service temperature range for HDPE pipe is reported to be -45.6 to 60^0 C (-50 to 140°F) for pressure service, and up to 82.2^0 C (180°F) for nonpressure service. The maximum operating service temperature for PVC is reported to be 60^0 C (140°F). The casing should be placed in the center of the borehole.

3.2.1.1.3. *Centralizers.* Centralizers center the casing in the borehole and must be a size appropriate for the casing and borehole. These are recommended for holes greater than 6 m (18 ft)

deep. Select centralizers made of material that will not lead to galvanic corrosion of the casing. Stainless steel centralizers are recommended with PVC or stainless steel casing.

3.2.1.1.4. *Screen.* The bottom two-thirds of the well should be screened using either a perforated or slotted casing. However, if the cover system does not contain a geomembrane, the casing should extend a minimum of 3.048 to 4.572 meters (10 to 15 feet) into the waste. Perforated pipe with 15 mm (0.5 inch) diameter holes spaced at 90 degrees every 0.15 to 0.3 m (6 to 12 inches) may be used. Slotted or continuous wrap screen may also be used. Continuous-wrap screen is preferred because the increased open area reduces the pressure drop across the screen and, therefore, reduces energy costs for the blower. Slot size should generally be a minimum of 2.5 mm (0.10 in.) but should be as large as possible to reduce the vacuum drop across the screen. End caps consistent with the screen type should be specified for the bottom of the well screen.

3.2.1.1.5. *Gravel Pack.* A gravel pack should be placed around the screen. The gravel pack should extend a minimum of .3 m (12 in.) above the end of the screen. The gradation of the gravel pack will be dependent on the gradation of the waste surrounding the well and the diameter of the borehole. Typically, washed river gravel or crushed stone is used. AASHTO No. 57 stone has been specified on several USACE projects.

3.2.1.1.6. *Seal and Grout.* A 1.3 m (4 foot) layer of bentonite material is placed on top of the gravel. A 0.3 m (12 inch) layer of fine sand should be placed between the gravel pack and grout if bentonite grout is used. The remainder of the borehole can be backfilled with cement-bentonite grout or a granular soil. Figure 3.1 is an example of an active gas extraction well. A 0.3 m (12 inch) thick bentonite seal is sometimes placed on top of the granular soil layer just beneath the cover system.

3.2.1.1.7. *Slip Couplings.* Slip couplings are often used if settlement is likely to be severe. The slip coupling allows the well to telescope down as settlement occurs. A prefabricated boot should be used to attach any geomembranes in the landfill cover to the gas vent pipe. This will help minimize leakage of atmospheric air into the landfill.

3.2.1.2. *Passive Gas Vent Well Design.* A passive gas vent well should be similar in design to an active extraction well. The well should be constructed of PVC or HDPE and should be a minimum of 100 mm (4 inches) in diameter. The pipe should be placed in the center of a 300 - 600 mm (1 to 2 foot) diameter borehole and backfilled with gravel to a level of 3 foot (.3 to 1 m) above the perforated or slotted section. The remainder of the hole should be backfilled in a fashion similar to an active gas vent well. Figure 3.2 is an example of a passive gas vent well.
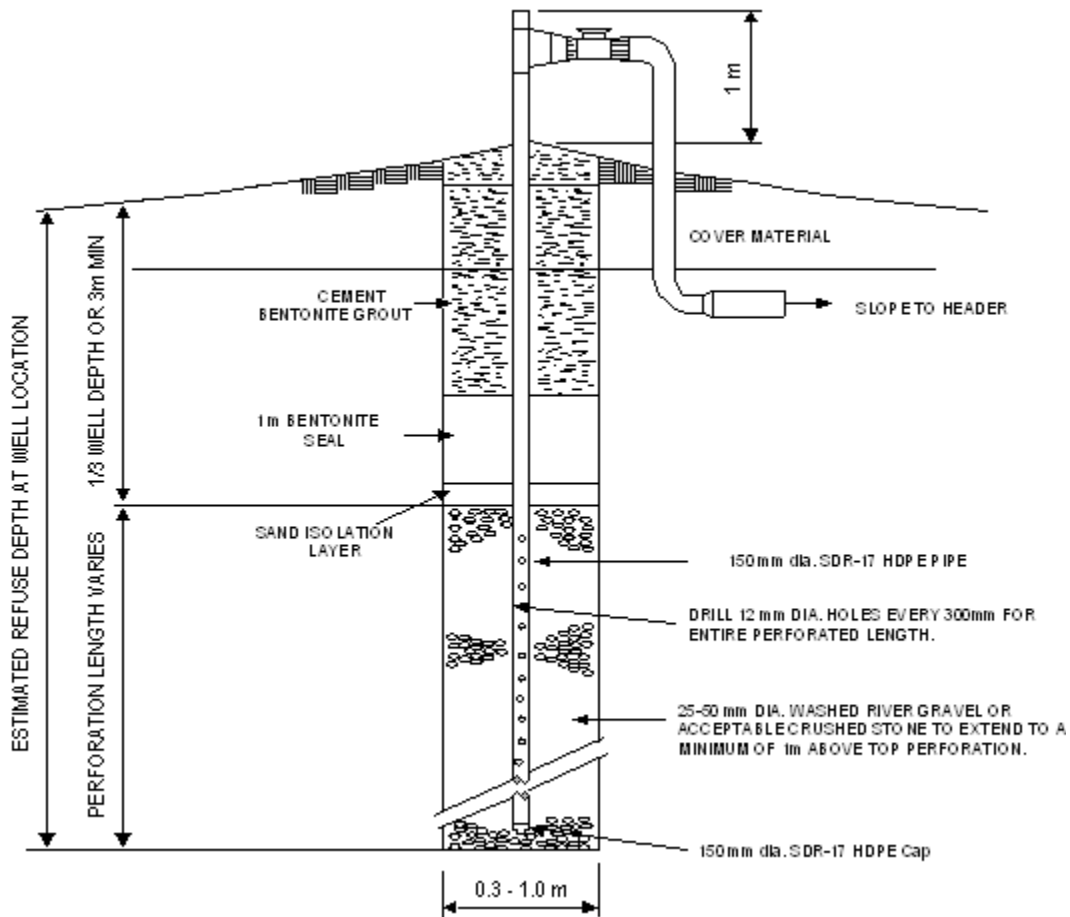
Figure 3.1. Typical Landfill Gas Extraction Well.

3.2.2. *Blanket Collection Systems.* The EPA recommends that continuous blanket collection systems constructed of sand or gravel be a minimum of 0.3 m (12 inches) in thickness and located below the impermeable barrier layer. A geosynthetic blanket with equivalent transmissivity properties can also be used. A continuous blanket system will allow free movement of gases to either collection or outlet pipes. Vertical outlet pipes transport the collected gases from beneath the landfill cover. The number of vent pipes should be minimized and are normally spaced about 60 m (200 ft) apart. This provides approximately one vent per acre. Perforated horizontal collection pipes can also be incorporated into the design of either passive or active blanket systems. A geotextile filter layer may be required to prevent clogging of the gas collection blanket material. Continuous blanket systems are effective in preventing excessive pressure from building up beneath the low permeability layer. They are less effective in preventing off-site migration of gas since there are no wells extending into the refuse. Gas wells or perimeter trenches should generally be used if off-site migration of gas is a concern.
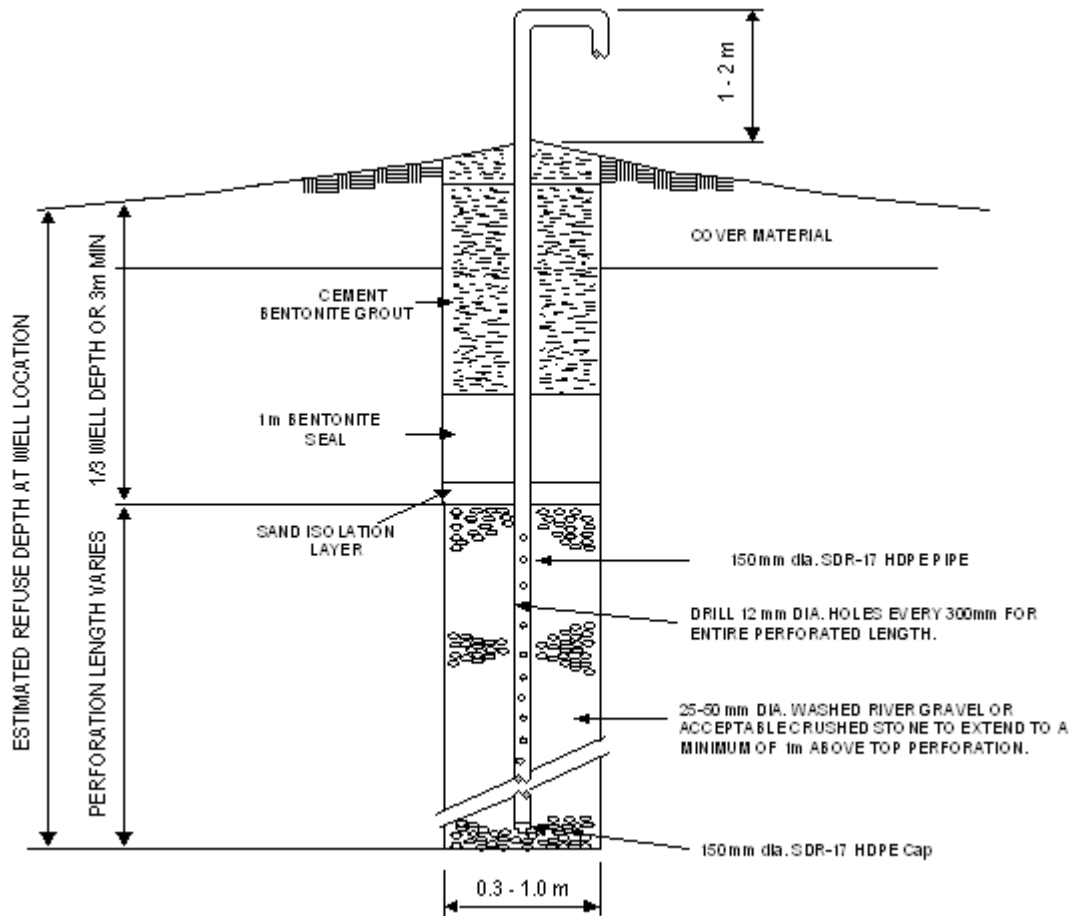
Figure 3.2. Passive Gas Vent Well.

3.2.2.1. *Granular Blankets.* The design of a granular collection blanket system requires choosing an appropriate material for use in the gas collection layer and determining the layer thickness. Typically, the minimum thickness is 0.3 m (12 inches). Granular material should have minimum fines to facilitate the flow of collected gas. AASHTO No. 57 stone is frequently specified for granular gas collection layers due to the general availability of this material. Geotextiles are often used to separate the granular blanket from other soils and refuse.

If large diameter (> 12.5 mm [0.5 in.]) or angular materials are used for the gas collection layer, overlying geomembranes should be protected with a geotextile or soil cushion layer. Geotextile cushion layers typically have a minimum weight of 0.4 kg/sq m (12 ounces/sq yard). Details regarding cushion layer design are given in Design Methodology for the Puncture Protection of Geomembranes (Wilson-Fahmy et al. 1996). Figure 3.3 shows a typical cross-section of a granular blanket gas vent layer.
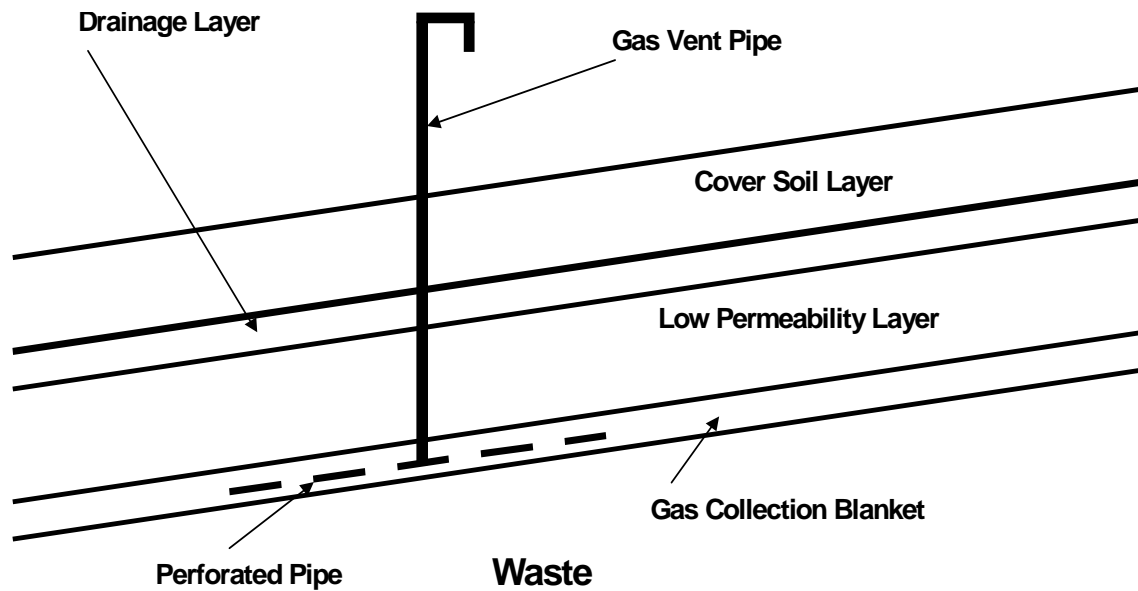
Figure 3.3. Gas Collection Blanket.

3.2.2.2. *Geosynthetic Blankets.* Geosynthetic gas collection systems have often been used to replace granular materials because they require less space and are easier to construct. A geosynthetic gas collection system typically consists of a three-dimensional geonet drainage core with a geotextile fabric attached to one or both sides. The geotextiles act as a filter/separator from adjacent layers of waste and soil. Geonets typically range from 5.0 to 8.0 mm (0.20 to 0.30 in.) in thickness but can be considerably thicker.

Thick nonwoven needlepunched (NWNP) geotextiles have also been used as gas collection blankets. However, they are effective only for very low volumes of gas and for low normal stresses. For these reasons, geonets/geocomposites are almost always preferred over geotextiles alone.

An example of a gas vent relief flap is shown in Figure 3.4. This flap design can be used with passive gas collection blanket systems where pipes that extend above the surface of the landfill are undesirable. The flap design configuration is only applicable where very low rates of gas generation are anticipated.
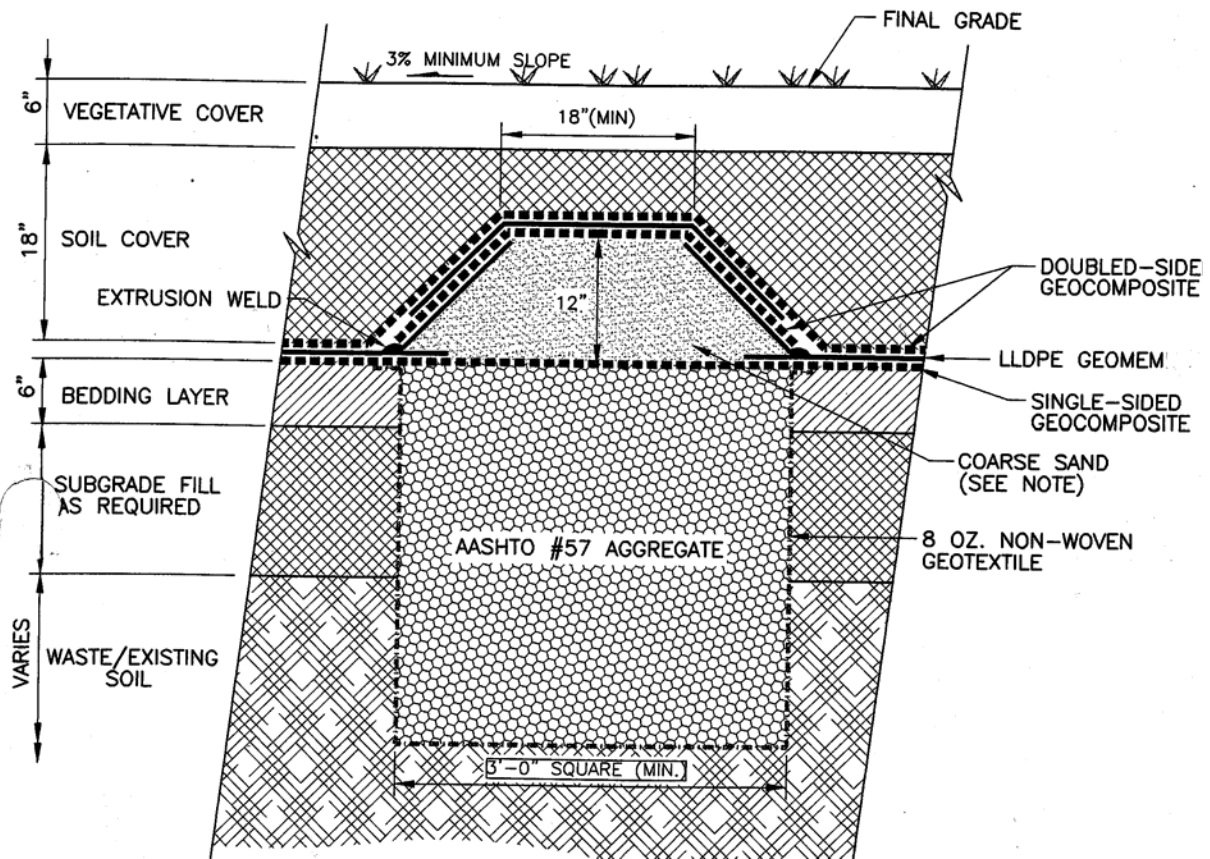
Figure 3.4. Gas Vent Relief Flap.

3.2.3. *Trenches.*

3.2.3.1. *Perimeter Trenches.* A trench can be constructed around the perimeter of a landfill to prevent the off-site migration of gas. The trench should extend from the ground surface to an impermeable geologic strata or the ground water table. The feasibility of installing a gas collection trench is dependent on the depth to the impermeable strata, the excavatability of the material into which the trench is being placed, and fluctuations in the ground water table. Collection trenches are typically 0.9 m or more (3ft or more) wide and are filled with gravel such as AASHTO No. 57 stone. Effectiveness can be improved by installing a 1.0 to 1.5 mm (40 to 60 mil) geomembrane on the outside wall of the trench. A protective geotextile should be placed between the collection rock and the geomembrane to prevent damage to the geomembrane. Seaming of geomembranes sheets within the trench is difficult and must be done using trench boxes to protect workers. A low permeability cover should be placed over the top of the collection trench to prevent precipitation from getting into the trench and saturating the collection rock. Figure 3.5 is an example of a perimeter gas collection trench.
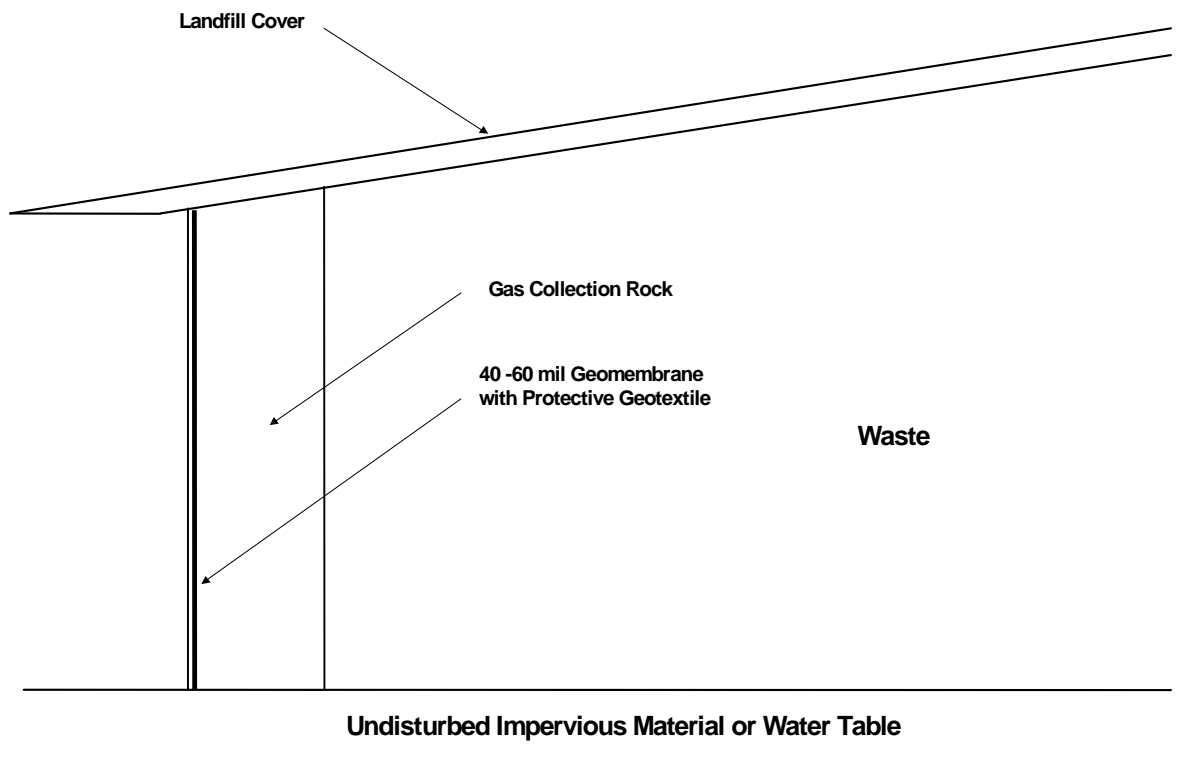
Figure 3.5. Perimeter Collection Trench.

3.2.3.2. *Surface Collection Trenches.* For landfills where the waste materials are relatively shallow (less than 12 m [40 ft] in depth), surface collection trenches are sometimes used to collect landfill gas. The trenches are typically excavated 0.5 to 1 m (1.5 to 3 ft) into the waste. The trenches are then lined with a geotextile and filled with rock. A perforated pipe is often placed within the rock to increase flow capacity. The trenches should be spaced approximately 60 m (200 ft) apart and are usually not interconnected. Vertical vent pipes are located at the ends of the trench, or at high points, and spaced 60 m (200 feet) apart for passive vent trenches. Gas is removed from active vent trenches using a series of header pipes. This will allow for individual lines to be valved independently for future system control and balancing.

3.2.3.3. *Horizontal Trench Collection Systems.* An example of a horizontal trench collection system is shown in Figure 3.6. This type of collection system can be installed during the placement of waste in an active landfill and is; therefore, not applicable to the closure of old landfills.
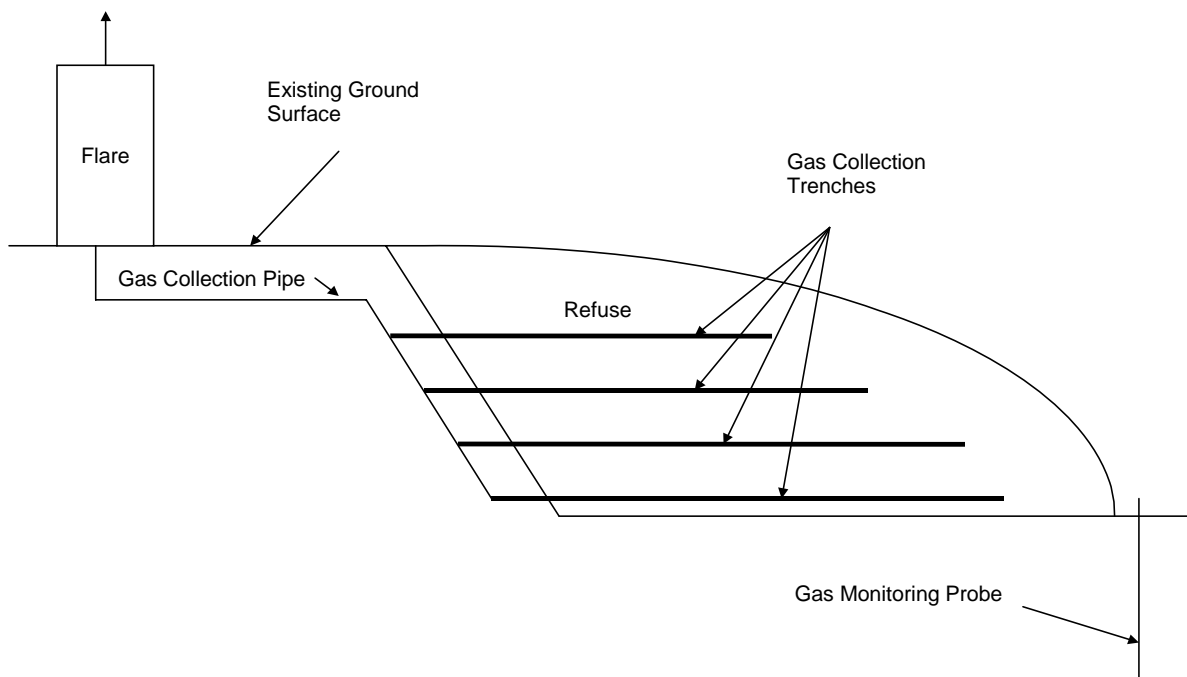
Figure 3.6. Horizontal Trench Collection System.

3.3. **Gas Monitoring Probes.**

3.3.1. *General.* Gas monitoring probes are used in conjunction with both active and passive systems to detect landfill gases that are migrating off-site. The regulatory compliance point is typically the property boundary. The maximum acceptable concentration of methane in the probes is typically 0.5 to 5 percent. Increased monitoring and/or modifications to the operating procedures of the landfill gas collection system are usually required if methane concentrations exceed acceptable levels. Gas samples may be also be analyzed for volatile organic contaminants to determine if there is a need to perform a soil gas survey to evaluate the soil vapor intrusion pathway.

3.3.2. *Design Considerations.* Gas monitoring probes are installed by placing a borehole into the ground to at least the same depth as the deposited waste. A 1.9 to 5.1 cm (0.75 to 2 inch) diameter perforated PVC pipe is placed into the hole and the space between the borehole wall and pipe is filled with sand or gravel. The sand and gravel layer should generally begin at least 1.5 m (5 feet) below the ground surface to reduce the potential for leakage of atmospheric air into the probe. A bentonite seal is placed above the filter pack and cement-bentonite grout is typically placed above the bentonite seal. Additional information on the design of gas monitoring probes can be found in EM 1110-1-4001, Soil Vapor Extraction and Bioventing.

3.3.2.1. It may be best to initially install probes deep enough to verify the water table and to assess stratification. Subsequent probes should then be placed above the water table in relatively

permeable strata that is likely to be a good conduit for the movement of methane. It is advisable to install gas probes at various depths where the unsaturated layer adjacent to deep landfills is thick.

3.3.2.2. Probes are typically placed around the perimeter of the landfill at a maximum spacing of 150–300 m (500–1000 ft), although they may be closer, depending on site specific factors such as adjacent land use, soil properties, and migration potential. At some sites, probes may be closely spaced, every 30–60 m (100–200 ft), if there are buildings near the landfill. Each probe must be permanently marked or tagged with an identification number to ensure data is accurately recorded.

3.3.2.3. Probes may be driven into the ground if they are going to be used to monitor strata that are less than 15 feet below the ground surface.

3.3.3. *Monitoring Devices for Structures.* Basements and crawl spaces of buildings located near landfills are potential collection points for methane. Methane that collects in these confined spaces can create a potential explosion hazard. An explosimeter should be used to periodically monitor these confined spaces for explosive conditions. Federal and state regulations require that explosive concentrations of methane in structures on and off the landfill must not exceed 25% of the LEL (12.5% by volume). Corrective actions are often initiated if the monitor detects methane at concentrations as low as 10 percent of the LEL. In addition to monitoring for explosive gases, O_2 monitoring should be performed during entry into confined spaces.

Note that structures that actually are part of the LFG control system (e.g. piping, vaults) are excluded from this requirement.

3.4. **Cover Penetrations**

3.4.1. *General.* Penetrations through the landfill cover are required for gas vents, monitoring probes, and for other purposes. Geomembranes should be attached to the penetrating pipe in a way that ensures a watertight seal but still allows for movement from settlement or horizontal displacement. Geomembranes are generally attached to penetrations using a boot that attaches to the pipe.

3.4.2. *Design Considerations.* Most geomembrane manufacturers have their own typical penetration details. Therefore, in many cases, it is only necessary to show locations of the penetrations on the drawings and note that penetration details must be in accordance with approved geomembrane manufacturer's details. ASTM D 6497 - *Mechanical Attachment of Geomembrane to Penetrations or Structures* can also be referenced when specifying penetration requirements for geomembranes. Geosynthetic clay liner (GCL) penetration details should also be as recommended by the GCL manufacturer. Pipes that penetrate deeply into the waste material are likely to settle at a different rate and to a smaller magnitude than the adjoining landfill cover. The differential settlement between the pipe and the cover system creates stress concentrations at the boot

connection that can tear the geomembrane away from the pipe. Slip couplings are typically used in this situation to allow differential movement while maintaining a watertight seal.

3.5. **Header Piping**

3.5.1. *General.* Header piping is used for active systems to transport gas from the collection wells to the flare. The piping system will typically have several branches. Multiple extraction wells are attached to each branch and valves are used to control the amount of flow coming from individual wells and branches. The number of low points in the header should be minimized and the flare should be located at a relative low point to aid in condensate collection within the header pipe. The piping can be placed on the landfill surface or it can be buried. In most instances, the header pipe should be buried to minimize the risk of damage from maintenance equipment and vandalism. Burying the header pipe also reduces the potential for blockage due to condensate freezing in the pipes. Buried header pipes are typically located above the geomembrane in the cover system. They should typically be a minimum of 150 mm (6 inches) of bedding material between the geomembrane and the header pipe. In some instances a marker tape has been installed approximately 150 mm (6 inches) above the pipe as a warning to maintenance workers who may be excavating into the landfill cover. Heat tracing can also be used to ensure condensate does not freeze in locations were the pipe cannot be installed below frost depth.

Above ground header pipes should only be considered where differential settlement of the landfill surface will result in reverse grades along the header pipe. Above ground pipe will need to be supported and sloped so that there is positive drainage to condensate collection pots. Placement of header pipe on the landfill surface is problematic in cold climates due to freezing condensate clogging the header. Above ground headers also make mowing and other maintenance activities more difficult.

3.5.2. *Design Considerations.*

3.5.2.1. *Pipe Material Options.* Header pipes are typically made of HDPE or PVC. PVC pipe is more susceptible to damage due to differential settlement than HDPE pipe because PVC is more rigid and brittle. It is also more vulnerable to ultraviolet (UV) radiation and low temperatures, 4°C (40°F), than HDPE pipe. PVC pipe must be painted with UV inhibitive paint if it is to be exposed to direct sunlight. PVC header pipe is easier to install than HDPE pipe because it can be solvent welded. HDPE pipe must be heat fusion welded which is more time consuming and expensive.

3.5.2.2. *Pipe Slopes.* Condensate collection points should be located at low points in the header pipe system to prevent blocking of the pipe with condensate. Depending on local regulations, condensate is sometimes allowed to drip back into the waste either through the wellheads or a separate percolation drain where possible. Header pipes should be sloped according to the following criteria:

	In direction of gas flow	Opposite direction of gas flow
On Landfill	2% slope	4% slope
Off Landfill	1% slope	3% slope

3.5.2.3. *Pipe Size.* The header piping should be sized to provide for minimal head losses and additional capacity, should supplementary extraction wells be required at a later date. Pipes should be sized for approximately 25 mm (1 inch) of water column pressure drop per 30 m (100 ft) of pipe. This will give a good balance between blower and piping cost. Condensate will flow along the bottom of the header piping and is another consideration when sizing LFG header pipes. LFG velocity should be limited to 12 mps (40 fps) when the LFG and condensate are flowing concurrently so that the condensate will condense on the LFG header piping side walls. LFG velocity should be limited to 6 mps (20 fps) when condensate flow direction is opposite that of the LFG to avoid the condensate damming up and blocking the flow of LFG.

3.5.2.4. *Flexible Connections.* Flexible hoses are commonly used at wellheads, header and lateral pipes, pump stations, knock-outs, main lines, and at other connection points where there is expansion, contraction, and pipe movement due to landfill settlement. Flexible connections prevent excessive stress, which is one of the most common causes of gas conveyance line failure. Flexible hoses must be designed to withstand system pressures, and deterioration due to condensate and UV radiation. Flexible hose is typically constructed from a helix of stainless steel wire which is encapsulated within inner and outer ply's of polyester fabric and impregnated with silicone rubber that is UV-resistant. The hose is typically held in place with stainless steel bands. Flexible hose can also be welded or glued to some types of plastic pipe (PVC, CPVC, and ABS plastic pipe). The hose should be installed such that there are no low spots where condensate can accumulate and block the flow of gas.

3.6. **Valves**

3.6.1. *General.* Valves are utilized in LFOG collection systems for flow rate control and on/off control. A typical system will have a flow control valve on each extraction head. The valves may be manually controlled or automatically actuated by an electric or pneumatic power source. Pneumatic actuators tend to be simpler and less costly than electric actuators particularly for explosion-proof applications. For the closure of old landfills, LFOG collection systems often do not rely on automated control valves. The selection and layout of valves in the LFOG system should be carefully evaluated during the design process to ensure that the level of control provided in the system is consistent with projected O&M needs. The following considerations should be given when selecting valves.

3.6.1.1. *Temperature Range.* Valves must operate safely in the temperature and pressure range of the system. PVC valves are prone to failure at low temperatures, therefore, lined metal or

HDPE valves are preferable for cold-weather service. In some situations, valves must be insulated and/or heated to prevent condensation.

3.6.1.2. *Flow Capacity and Pressure Range.* The operating range of a control valve must match the flow control requirements of the application. A flow control valve functions by creating a pressure drop from the valve inlet to outlet. If the valve is too large, the valve will operate mostly in the almost closed position, giving poor sensitivity and control action. If the valve is sized too small, the upper range of the valve will limit flow.

3.6.1.3. *Strength and Durability.* Because LFG systems consist of multi-phase flow, valves and fittings should be constructed of stronger and more durable materials than might normally be required in single-phase water or gas service. The condensate can often form slugs of water drawn through the system at relatively high speed. This can result in a "water hammer" or impact loading on the valves and fittings.

3.6.1.4. *Frictional Losses.* Valves must not create excessive frictional loss when fully opened.

3.6.1.5. *Chemical Compatibility.* Valves must be chemically compatible with the liquid or air stream.

3.6.2. *Design Considerations.* Formulas and sizing procedures vary with valve manufacturer. Computations typically involve calculating a capacity factor (C_v), which depends on the flow rate, specific gravity of the fluid, and pressure drop. The designer calculates C_v at the maximum and minimum flow rates required. The calculated range of C_v values must fall within the range for the valve selected.

During the mechanical layout of the system, assure that the valves are accessible. Number and tag the valves. To avoid ambiguity, refer to the valves by number in the design and in the O&M manual. The following is a brief description of several valves commonly employed for LFOG collection and treatment systems:

3.6.2.1. *Gate Valve.* Gate valves are primarily designed to serve as isolation valves. In service, these valves generally are either fully open or fully closed. When fully open, gas flow through the valve is in a straight line with very little resistance. As a result, the pressure loss through the valve is small. Gate valves are frequently used at well heads to control flow from individual wells.

3.6.2.2. *Butterfly Valve.* Butterfly valves are used for both on/off and throttling applications at well heads and for other applications. The butterfly valve is characterized by fast operation and low pressure drop. Flow is controlled with a rotating disk or vane. This valve has relatively low friction loss in the fully open position. Butterfly valves can more accurately control a flow rate in gas or multi-phase service than gate valves.

3.6.2.3. *Globe Valve.* Used for on/off service and clean throttling applications, this valve controls flow with a convex plug lowered onto a horizontal seat. Raising the plug off the seat allows for fluids to flow through. Globe valves can more accurately "pinch" or control a flow rate in gas or multi-phase service than butterfly valves.

3.6.2.4. *Ball Valve.* Also used primarily for on/off control and some throttling applications, the ball valve uses a rotating ball with a hole through the center to control flow. Ball valves can be operated quickly and result in negligible resistance to flow when fully open.

3.6.2.5. *Diaphragm Valve.* A multi-turn valve used to control flow in both clean and dirty services. The diaphragm valve controls flow with a flexible diaphragm attached to a compressor and valve stem.

3.6.2.6. *Needle Valve.* A multi-turn valve used for precise flow control applications in clean services, typically on small diameter piping. Needle valves have relatively high frictional losses in the fully open position.

3.6.2.7. *Check Valve.* Check valves are used to allow flow in one direction only. Check valves are sometimes needed between the well and the pump to prevent air from being drawn backward when the pump is shut off. Under high vacuum, this can affect a variety of in-line readings, particularly if a carbon canister is being used for air treatment.

3.6.2.8. *Sample Valve.* Quick connect sample valves are used on gas monitoring probes and well heads to check pressure or gas constituent concentrations.

3.7. **Well Heads.** Well heads for passive gas vents are typically configured to prevent precipitation and wildlife from entering the well. Wellheads for active well systems typically include control valves to increase and decrease the flow of gas from individual wells and flexible connections to compensate for differential movement between landfill gas wells and header pipes. The well head will also include sampling ports to monitor gas concentrations, temperature, velocity, and pressure. Specialty companies have created data collection ports that can be easily attached at each well head to allow easy collection of this data. Portable measuring equipment is attached to the measuring ports to collect the required data.

3.7.1. *Flow Rate Measurement.* Pitot tubes and orifice plates are the two most common methods of measuring flow at a well head of a landfill gas collection system.

3.7.2. *Orifice Plate.* An orifice plate is a thin plate with a circular hole in the center (See Figure 3.7). The plate is placed within a pipe perpendicular to the direction of gas flow. Orifice plates are used to determine gas flow rate by measuring the differential pressure across the orifice plate. They are generally less expensive to install and manufacture than the other commonly used

differential pressure flow meters; however, nozzle and venturi flow meters have the advantage of lower pressure drops. Equations for orifice meters have the advantage of no Reynolds Number upper limit for validity. An orifice flow meter is typically installed between flanges connecting two pipe sections. Gas flow calculations include an expansion factor. The expansion factor accounts for the effect of pressure change on gas density as gas flows through the orifice.
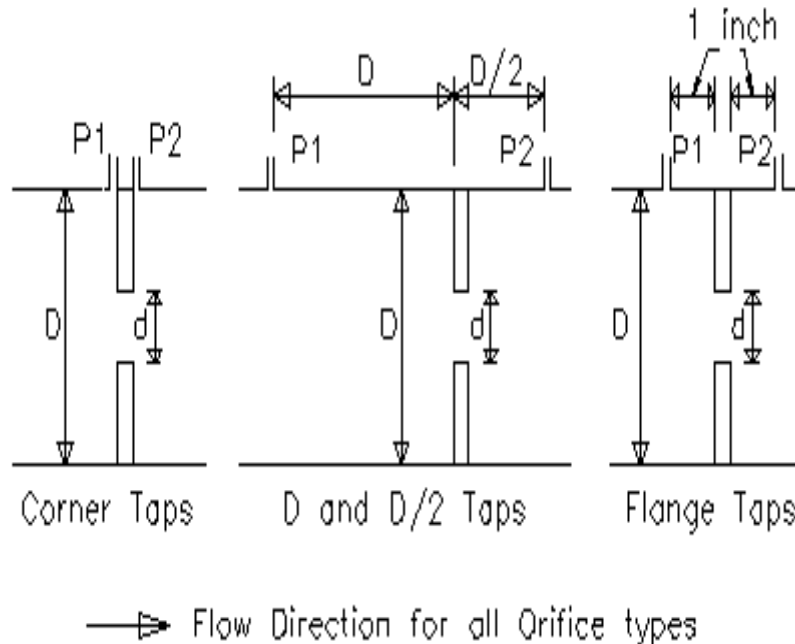
Figure 3.7. Orifice Plate Flow Measurement Device.

3.7.3. *Pitot Tube.* A pitot tube is used to measure velocity based on a differential pressure measurement as shown in Figure 3.8. The Bernoulli equation models the physical situation very well. A pitot tube can also give an estimate of the flow rate through a pipe or duct if the pitot tube is located where the average velocity occurs. The average velocity times the pipe cross sectional area equals the flow rate. Often, pitot tubes are negligently installed in the center of a pipe. This gives the velocity at the center of the pipe, which is usually the maximum velocity in the pipe, and could be twice the average velocity. See ACGIH® Industrial Ventilation: A Manual of Recommended Practice for additional information on the use of Pitot tubes.
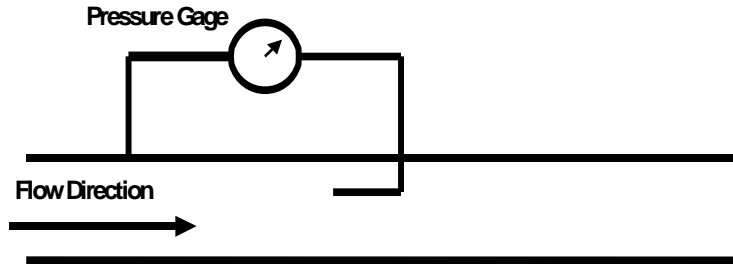
Figure 3.8. Pitot Tube Flow Measurement Device.

Bernoulli's equation is used to estimate flow velocity based on pressure measurements from a Pitot tube:

$$V = [2\ (P_T - P_S)/\rho]^{0.5}$$

where:

V	=	fluid velocity
P_T	=	total pressure
P_S	=	static pressure
ρ	=	fluid density.

3.8. **Header System Layout.**

   3.8.1. *General.* A header system can be constructed in three general configurations: branches, loops, or as a matrix. These layout options are shown in Figure 3.9. Branched systems consist of individual wells attached to a blower through the use of a header pipes and larger trunk lines. Branched systems are fairly common on small landfills where there are a limited number of wells. Looped systems ring the landfill and have the advantage of allowing gas to be pulled from an individual well from more than one direction, bypassing clogs in the header line. Looped systems will often incorporate branches off of the main loop to allow collection of gas from regions of the landfill that are not adjacent to the loop. The design objectives of the header system are as follows:

   • Create sufficient vacuum and flow from each extraction well to collect all landfill gas and prevent the off-site migration of gas.
   • Move the gas through the header system to the blower and flare.
   • Accomplish the first two objectives with the lowest possible capital and operating expenditures.

Pressure losses in the piping system are the result of friction losses and dynamic losses. Friction losses occur as gas flows through the header pipes. Dynamic losses result from things such as changes in flow direction (elbows and tees), pipe constrictions, valves, filters, knock-out pots, and

other restrictions within the piping network. The total pressure loss is the sum of the friction and dynamic losses.
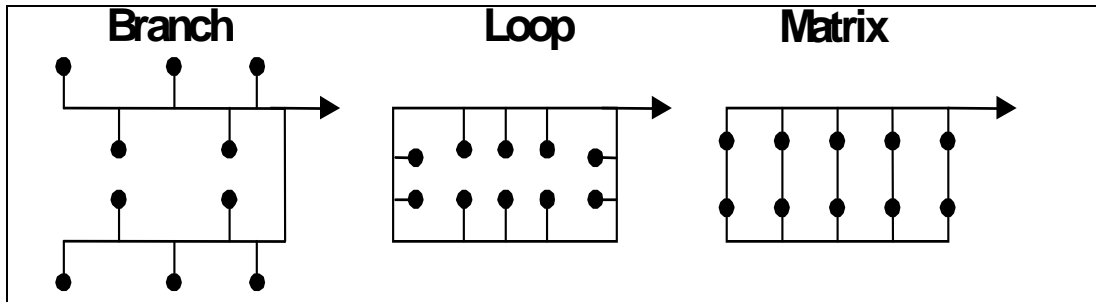
Figure 3.9. Header Layout Options.

3.8.2. *Design Considerations.* It is important to consider overall system pneumatics prior to designing and selecting individual system components. A suggested approach is briefly summarized below (Brown and Clister 1993):

3.8.2.1. *Step 1.* Determine the size and depth of the landfill.

3.8.2.2. *Step 2.* Determine the type of waste within the landfill and its associated gas generation rate.

3.8.2.3. *Step 3.* Estimate the Radius of Influence (ROI) and based on this ROI, layout the gas extraction wells and the header pipes.

3.8.2.4. *Step 4.* Develop a relationship for vacuum level versus airflow in the subsurface.

3.8.2.5. *Step 5.* Calculate the friction loss for the system components and piping for a range of flow rates.

3.8.2.6. *Step 6.* Develop a "system" curve by adding the frictional losses calculated in steps 4 and 5.

3.8.2.7. *Step 7.* Select a blower with an appropriate blower curve.

3.8.2.8. *Step 8.* Predict the flow rate and vacuum level from the simultaneous (graphical) solution of the blower curve and the system curve.

3.8.2.9. *Step 9.* Perform a network pressure analysis using the assumed well layout and equipment. Determine if the proposed system provides adequate vacuum and flow to all portions of the landfill.

3.8.3. *Subsurface Losses.* Subsurface losses are a function of the following:

- Waste permeability.
- Radius of influence of the well.
- Depth of waste.
- Gas extraction rate.
- Gas generation rate.

For large municipal solid waste landfills, subsurface losses can most accurately be quantified by performing pump tests. These tests determine the required vacuum needed to maintain a given flow rate. However, for older landfills such as those found at military installations, pump tests are not commonly performed as part of the design process. If pump tests are not performed, subsurface losses will need to be estimated based on existing conditions and past experience of the designer. Typically, the extraction well vacuum can be assumed to be 125 to 250 mm (5 to 10 inches) of water column.

3.8.4. *Pipe Losses.* Head loss through the header system components can be predicted for a range of flow rates. The most common method of predicting friction losses in straight pipes is to use the Darcy-Weisbach equation for incompressible fluids:

$$h_f = f\,(L/d)\,(v^2/2g)$$

where:

h_f = friction loss [ft (m) of water]
f = friction factor [dimensionless (dimensionless)]
L = pipe length [ft (m)]
d = inside pipe diameter [ft (m)]
v = average velocity of the flow [ft/s (m/s)]
g = gravitational acceleration [32.16 ft/s² (9.807 m/s²)]

Use of Darcy-Weisbach for gases is limited to systems with less than 10% compression without correction. The friction factor f is a dimensionless number that has been determined experimentally for turbulent flow and depends on the relative roughness of the interior of the pipe and the Reynolds number. Tables and charts have been developed to predict friction losses for a range of pipe materials and diameters.

3.8.5. *Losses in Valves and Fittings.* There are two primary methods for estimating head losses through valves and fittings:

- Look up k values in tables (where $k = f\,L/d$ and, therefore, $h_f = kv^2/2g$).

- Use tabulated values of equivalent length of straight pipe. For example, the resistance in a 150 mm (6 inch) standard elbow is equivalent to that of approximately 5 meters (16.5 feet) of 150 mm (6 inch) straight pipe.

3.8.6. *Losses at Flare Station.* Condensate collection tanks, flame arrestors and other equipment will typically result in applied head losses of around 125 mm (5 inches) of water column. The flare itself will exert a backpressure on the outlet side of the blower. This backpressure is typically around 250 mm (10 inches) of water column.

3.8.7. *System Analyses.* The friction losses from the subsurface, the straight pipe lengths, and the valves and fittings are added together to obtain the total friction loss at a given vacuum level. This calculation is repeated for several flow rates to establish a system curve. Note that these calculations are performed assuming that the valves are fully open.

The blower curve is then superimposed on the system curve. A specific blower should be selected based on mechanical, electrical, and pneumatic considerations. The blower curve is negatively sloped and the system curve is positively sloped. The predicted flow rate and vacuum level occur at the intersection of the two curves, representing the simultaneous solution of two equations.

The predicted flow rate must exceed the design flow rate to allow flow control of multi-well systems by valves located at individual wellheads. This adjustment causes an increase in vacuum level at the blower and a decrease in the total flow rate as shown in Figure 3.10. The designer must verify the new flow rate and pressure are within the operating range of the blower. Therefore, the operating point must be on the blower curve above the intersection of the blower curve and the system curve. For complex piping networks, it would be worthwhile to acquire software designed for this application.

3.8.8. *Simplified Pneumatic Design Procedure.* The following is a simplified design procedure taken from CES-Landtec Landfill Gas System Engineering Design Seminar courseware and can be used to estimate system vacuum and pressure requirements for the blower.

3.8.8.1. *Problem.*

3.8.8.1.1. Estimate the following:

Total system flow _____ cubic feet per minute (cfm)
Fan pressure _____ Inches of water column (in. w.c.)

3.8.8.1.2. Based on the specified flow and pressure of the gas collection system, select the "longest" pipe run (or path with highest resistance to gas flow) and calculate the Total Pressure Drop (TPD) from blower to extraction well:

Total pressure drop or fan pressure required = pipe friction + fitting losses + applied head losses
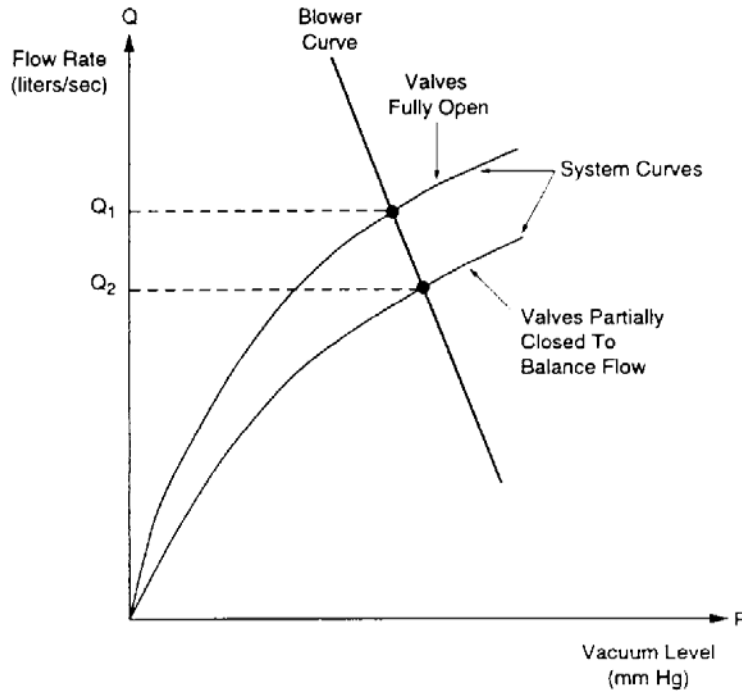
Figure 3.10. Typical Pneumatic Analysis.

3.8.8.2. *Determine Header Pipe Friction Loss.* Pipe friction can be calculated by multiplying the effected length of pipe (feet) times the Darcy friction factor found on the Moody Diagram. The following equation represents Darcy's Friction Loss:

$h_f = f\,(L/d)\,(v^2/2g)$

where:

h_f = friction loss [ft (m) of fluid]
f = friction factor [dimensionless (dimensionless)]
L = pipe length [ft (m)]
d = inside pipe diameter [ft (m)]
v = average velocity of the flow [ft/s (m/s)]
g_c = gravitational acceleration [32.16 ft/s² (9.807 m/s²)].
ΔP = $f\,(\rho_g/\rho_w)\,(L/d)\,(v^2/2g)$

where:

ΔP = pressure drop [in w.c./100 ft of pipe]
ρ_g = gas density [lb_m/ft^3]

ρ_w = water density [62.4 lb_m/ft^3]
L = 100 ft of pipe

and

$\Delta P = f\,(\rho_g/62.4\ lb_m/ft^3)\,(100/d)\,(v^2/2 * 32.16\ ft/s^2)$
$\Delta P = f\,(\rho_g/(62.4 * 2 * 32.16\ s^2\ lb_m/ft^2))\,(L/d)\,(v^2)$
$\Delta P = 0.000249\ s^2\ lb_m/ft^2\,f\,(\rho_g)\,(L/d)\,(v^2)$
1 pound-force/square foot = 0.1922216 inch of water [4 °C]
$\Delta P = 0.004789$ in w.c./100 ft of pipe $f\,(\rho_g\,L\,v^2/d)$

Total $\Delta P_{friction}$ = Header Friction Loss + Branch Friction Loss

3.8.8.2.1. Select length _____ (ft) of affected header pipe (L)

3.8.8.2.2. Obtain specified blower flow rate (Q) _____(cfm)
3.8.8.2.3. Determine pipe internal diameter as _____ in. or (_____ ft)

3.8.8.2.4. Use Continuity Equation ($Q = vA$) to calculate velocity as _____ (linear ft/min) or _____ (ft/s). Where multiple branches of header pipe exist, the flow must be estimated in each branch.

3.8.8.2.5. Calculate Reynolds Number (N_{RE}) using the following equation:

$$N_{RE} = \frac{Dv\rho}{\mu_e}$$

where:

D = pipe diameter (ft)
v = fluid velocity (ft/s)
ρ = fluid density (lb_m/ft^3)
μ_e = absolute viscosity (lb_m/ft s).

Reynolds Number = _____ Determine if the flow is turbulent or not. .

3.8.8.2.6. Determine the relative roughness of pipe materials (ε/D) as _____

3.8.8.2.7. Use Moody Chart to determine the Darcy friction factor by determining the relative roughness:

$f =$ _____(estimated)

Substituting into Darcy:

$$\Delta P = \frac{(\rho)(f)(100)(v)^2(27.7)}{(144)(D)(64.4)}$$

$\Delta P =$ _____ (in. w.c.) per 100 ft of pipe

Total friction loss for header pipe section = (Header pipe length _____ft / 100) x _____ΔP (in. w.c.) = _____in w.c.

3.8.8.3. *Determine Branch Pipe Friction Loss*

3.8.8.3.1. Select length _____ (ft) of affected branch pipe (*L*)

3.8.8.3.2. Obtain specified branch flow rate (Q) _____(cfm)

3.8.8.3.3. Determine pipe internal diameter as _____ in. or (_____ ft)

3.8.8.3.4. Use Continuity Equation ($Q = vA$) to calculate velocity as _____ (linear ft/min) or _____ (ft/s). Where multiple branches exist, the flow must be estimated in each branch.

3.8.8.3.5. Calculate Reynolds Number (N_{RE}).

$N_{RE} =$ _____ Verify if the flow is turbulent or not.

3.8.8.3.6. Determine the relative roughness (ε/D) as _____

3.8.8.3.7. Use Moody Chart to determine the Darcy friction factor using the appropriate relative roughness curve:

$f =$ _____(estimated)

Substituting into Darcy:

$$\Delta P = \frac{(\rho)(f)(100)(v)^2(27.7)}{(144)(D)(64.4)}$$

$\Delta P =$ _____ (or psi) per 100 ft of pipe

Total friction loss for branch pipe section = (header pipe length _____ft / 100) × _____ΔP (in. w.c.) = _____in. w.c.

Total Friction Loss = Header _____ + Branch _____ = _____(in. w.c.)

3.8.8.4**.** *Calculate Valve and Fitting Losses.* Locate all valves (ball, globe, angle etc.) and fittings (elbows, tees, reducers, etc.), which are in the "longest run" of piping and are points of resistance against flow from the extraction well to the blower.

Header Pipe Section (Darcy ΔP = _____in. w.c./100 ft of pipe):

Fitting Type	**No.**	**Size**	**Eq. Leng.**	**ΔP**
Gate Valve	____	____	_____	_____
Ball Valve	____	____	_____	_____
Check Valve	____	____	_____	_____
90° Standard Elbow	____	____	_____	_____
45° Standard Elbow	____	____	_____	_____
Standard Tee	____	____	_____	_____

Branch Pipe Section (Darcy ΔP = _____in. w.c./100 ft of pipe):

Fitting Type	**No.**	**Size**	**Eq. Leng.**	**ΔP**
Gate Valve	____	____	_____	_____
Ball Valve	____	____	_____	_____
Check Valve	____	____	_____	_____
90° Standard Elbow	____	____	_____	_____
45° Standard Elbow	____	____	_____	_____
Standard Tee	____	____	_____	_____

Compute the pressure drop from these sources using the following methods:

3.8.8.5**.** *Pressure Drop Due to Fittings.* Using PVC or HDPE pipe manufacturer's data, obtain "equivalent length of straight pipe" data for fitting types and sizes used in the "longest run." By multiplying the Darcy friction factor for the effected section of piping (i.e. the header or the branch, times the effected fitting's "equivalent length of straight pipe") the pressure drop across the fitting can be computed.

What follows is an example. Given: ΔP = 0.654 in. w.c./100 ft of pipe*

ρ = 0.065 lb$_m$/ft^3, μ_e = 8.14 × 10^{-6} lb$_m$/ft·s

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* Computed using Q = 800 cfm, D = 0.665 ft.

for smooth plastic pipe. Find the pressure drop due to two 8-inch 90° elbows and three 8-inch tees in the header pipe section. The solution is as follows.

3.8.8.5.1. Obtain pipe manufacturer's "equivalent length of straight pipe" data for 8-inch elbow and 8-inch tee:
For 8-inch, 90° elbow, equivalent length = 33.3 ft

For 8-inch tee, with flow through run, equivalent length = 16.5 ft.

3.8.8.5.2. Using $\Delta P = 0.654$ in w.c./100 ft of pipe for Q = 800 cfm in 6 in (0.665 ft ID) pipe.

Δp_{elbows} = (0.654 in. w.c.) x (33.3 ft/100 ft) × 2 = 0.436 in. w.c.

Δp_{tees} = (0.654 in. w.c.) x (16.5 ft/100 ft) × 3 = 0.323 in. w.c.

3.8.8.5.3. Compute $\Delta p_{fittings} = \Delta p_{elbows} + \Delta p_{tees}$
$\Delta p_{fittings}$ = (0.436 in. w.c.) + (0.323 in. w.c.) = 0.759 in. w.c.

3.8.8.6. *Pressure Drop Due to Valves.* The previous method used for fittings can also be used for valves if equivalent length data is available. If equivalent length data is not available the pressure drop due to valves can be computed using the following equation:

$$\Delta P_{valve} = (\frac{\rho}{62.4})(\frac{7.48\,Q}{C_v})^2$$

where:

ρ = fluid density (lb_m/ft^3)
Q = flow through valve (ft^3/min)
C_v = valve or fitting coefficient

C_v can usually be obtained from the valve manufacturer's data. If the fitting coefficient must be computed the following may be used:

$$C_v = \frac{29.9\,d^2}{\sqrt{K}}$$

where:

C_v = valve or fitting coefficient
d = pipe diameter (in.)

K = resistance coefficient*

The following is an example. Given are the following: $Q = 800$ cfm; $\rho = 0.065$ lb$_m$/ft^3; $d = 8$ inches; $K = 106.5$, $62.4 =$ lb$_m$/ft^3 for water Find ΔP_{valve}. Solution:

$$\Delta P_{valve} = (\frac{0.065 \text{ lb}_m/\text{ft}^3}{62.4})(\frac{(7.48\ )(800\text{ft}^3/\text{min})}{\frac{29.9\ (8\text{ inch})^2}{\sqrt{106.5}}})^2$$

$\Delta P_{valve} = 1.09$ in. w.c.

3.8.8.7. *Calculate/Determine Applied Head Losses.* Applied head losses for gas control systems usually consist of the following:

- Extraction Well Vacuum   _____ in. w.c. (typical: 5–10 in. w.c.)
- Flare Backpressure   _____ in. w.c. (typical: 10 in. w.c.)
- Inlet Scrubber Vessel   _____ in. w.c. (typical: 2–5 in w.c.)

Total Applied Head Loss   _____ in. w.c.

3.8.8.8. *Compute Total Head Loss from Extraction Well to Flare.*

- Pipe Friction Head Losses _____ in. w.c.
- Fitting and Valve Losses   _____ in. w.c.
- Applied Head Losses   _____ in. w.c.

Total Pressure Drop   _____ in. w.c.

3.9. **Condensate Collection**

3.9.1. *General.* An important element in the design of a gas collection system is condensate management. Condensate is formed when warm LFG cools during transport or processing. LFG is typically warm and saturated when extracted from the moist environment of a landfill. As the gas travels through the header pipes, it cools, which reduces its moisture holding capacity. The quantity of condensate generated in a LFG collection system is a function of how much LFG is being extracted, the vacuum or pressure being exerted on the LFG, and the magnitude of the temperature change. To prevent this water from blocking the header lines, low points in the piping system should have condensate knock-out tanks. A knock-out tank is also typically located within the flare station to help prevent condensate from damaging the blower and other equipment located in the

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* Normally provided by fitting/valve manufacturer.

flare station. Knock-out tanks are specifically designed to promote the formation of liquid droplets and to separate these droplets from the gas flow. Knock-out tanks are periodically pumped out. On large landfills, condensate collection can be automated with pumps and a piping system that carries the condensate to a central location where it can be stored and treated.

When laying out the header piping system, condensate collection should be an important consideration. If feasible, the header piping can follow surface water management berms. This will facilitate installation and maintenance of the header lines. Settlement of the waste must also be considered when laying out the header system. Excessive settlement may result in reverse grades that trap condensate and plug the header lines. Additional condensate collection points should be placed in areas where a large amount of settlement is anticipated or where header lines have very little slope.

    3.9.2. *Design Considerations.* Some reasonable assumptions may be made when estimating condensate generation:

- LFG temperature at the wellhead is the warmest.
- The header pipe is installed below the frost line.
- LFG temperature depends on the distance traveled in the buried header pipe and the thermal conductivity of the header pipe.
- LFG is completely saturated with water vapor.

The quantity of LFG condensate will vary throughout the year. Typically, during the winter, condensate formation will be at its highest. A psychometric chart is a graphical representation of the thermodynamic properties of moist air. These tables can also be used to provide information on the amount of moisture in landfill gas even though LFG is generally a combination of methane and carbon dioxide. The following set of example calculations demonstrates how to estimate the quantity of condensate that will be generated.

    3.9.2.1. *Sample Calculation—Condensate Quantity.* Estimate the rate of condensate generation for a section of header pipe of a landfill gas extraction system. The flow rate within the header pipe is 500 cfm (236 L/s). The system is under a vacuum of 40 inches of water (91.4 kPa). This is equivalent to an absolute pressure of 0.9 atmospheres. The average ambient temperature of the soil surrounding the header pipe is 50^oF (283 K). The solution is as follows:

Assume the gas extracted from the landfill is 50% methane and 50% carbon dioxide and is at 100% relative humidity. Assume the gas temperature within the pipe drops from 90^oF (305 K) as it exits the landfill to 70^oF (294 K) as it travels through the header pipe. The water holding capacity of the

landfill gas will drop as the temperature of the gas drops and can be estimated from a psychrometric chart.*

Conc. of water vapor = 0.030 kg water/kg landfill gas (at 305 K)

Conc. of water vapor = 0.015 kg water/kg landfill gas (at 294 K)

Subtracting gives:

Potential Condensate = 0.015 kg water/kg landfill gas

The ideal gas law can be used to estimate the density of the gas passing through the header pipe:

Density = $P M/R_U T$

where:

P = absolute pressure within header pipe
M = molecular weight of landfill gas
= 0.5 (molecular weight methane) + 0.5(molecular weight of carbon dioxide)
= 0.5 (16) + 0.5 (44) = 30 kg/kg-mole
R_U = Universal gas constant = 0.0821 L-atm/g-mole K
T = temperature.

Density = $P M/R_U T$ = [(0.9 atm) × (30kg/kg-mole)] / [(0.0821 L-atm/ g-mole K) × (294 K) × (1,000 g-mole/kg-mole)]
Density of landfill gas = 1.12×10^{-3} kg/L

The flow rate times the concentration of the condensate yields the following condensate generation rate:

(0.015 kg water/kg LF gas) × (1.16×10^{-3} kg/L) × (236 L/s) × (86,400 s/day) × (1 L/kg) = 356 L/day

3.9.2.2. *Condensate Pumps.* Several options exist for dealing with condensate. Condensate generated can be drained back into the landfill, if allowed by the approving regulatory agency, the. If the condensate must be collected and treated, two options exist: 1) The condensate can be collected in several large tanks located throughout the header system; or 2) the condensate can be

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* Most psychometric charts are created for higher pressures than are typically found in the header pipes of a LFG collection system. However, using these charts will generally not introduce large error when estimating condensate generation.

periodically removed from several smaller collection tanks using pumps and header pipes. In this scenario, the condensate will typically be stored in a larger tank prior to off-site disposal.

The condensate generation rate must be estimated to determine the condensate pump required. Typical condensate sump pumps are rated from 10-30 gpm with 1 to 2 inch discharge piping. The preferred design velocity in the discharge is approximately 5 feet per second (between 2 and 8 feet per second). Friction losses in the piping are estimated by the Hazen-Williams method, valid only for water at ordinary temperatures (40 to 75 ^{o}F).

$$h_f = L \, (V / K \, C \, R_h^{0.63})^{1.852}$$

$$h_f = L \, (V / 1.318 \, C \, R_h^{0.63})^{1.852} \text{ (English units)}$$

where:

    h_f = frictional head loss (ft H_2O)
    L = pipe length (ft)
    V = velocity (2 - 8 ft/s)
    K = unit conversion factor = *1.318*
    C = Hazen-Williams roughness coefficient (80 – 150).
    R_h = hydraulic radius (ft) = d (in)/48

Substituting:

    V = $Q / 448.8312 / \, (d/24)^2$
    V = $0.4085 \, Q / d^2$

where:

    Q = flow (gallons per minute)
    d = inside diameter of pipe (inches).
    h_f = $L \, [(0.4085 \, Q / d^2) / 1.318 \, C \, (d/48)^{0.63}]^{1.852}$
    h_f = $10.458 \, L \, Q^{1.852} / C^{1.852} \, d^{4.87}$ (English units)

    h_f = $L \, (V / K \, C \, R_h^{0.63})^{1.852}$

    h_f = $L \, (V / 0.8492 \, C \, R_h^{0.63})^{1.852}$ (SI Units)

where:

    h_f = frictional head loss (m H_2O)
    L = pipe length (m)
    V = velocity (0.61 - 2.44 m/s)
    K = unit conversion factor = *0.8492*
    C = Hazen-Williams roughness coefficient (80 – 150).

R_h = hydraulic radius (m) = d (m)/4

Substituting:

V = $Q / \pi (d/2)^2$
V = $1.2732\ Q / d^2$

where:

Q = flow (m^3/s)
d = inside diameter of pipe (m).

h_f = $L\ [(1.2732\ Q / d^2) / 0.8492\ C\ (d/4)^{0.63}]^{1.852}$
h_f = $10.672\ L\ Q^{1.852} / C^{1.852}\ d^{4.87}$ (SI Units)

3.9.2.2.1. Determine if longest run of condensate pipe is adequately sized, such that total head loss Δh_{total} is 10 percent of the condensate sump pump's specified pressure.

3.9.2.2.2. Use the Hazen-Williams equation to estimate head loss.

3.9.2.2.3. Compute the total head loss from pump to receiver tank (assume 20% loss due to fittings):

Δh_{total} = (h$_f$ _____ ft/100 ft of pipe) ×(Total Length of Run (ft) + 20%)

3.9.2.2.4. Determine if Δh_{total} is approximately 10% of specified pump pressure.

Δh_{total} _____ psia < / = / > .10 ×h$_{pump}$ _____ psia

3.9.2.2.5. Other design considerations include the following:

- Sumps should be located at lowest elevation with respect to gas header and branches from which condensate will be collected.
- All condensate pipes should have at least a 3 percent slope (if possible) to promote drainage.
- Condensate pipe should be run with air supply lines and gas collection lines to provide better access for maintenance and protection of pipe (if PVC or HDPE is used).
- Most condensate collection system sump pumps use compressed air versus electric powered. If a compressed air system is used, air lines and air compressors will need to be sized as part of design process.
- Condensate collection systems are normally discharged to regional waste water treatment systems with an amendment to the operator's NPDES or sewer use permit. However, depending on the amount of condensate and its characteristics, pretreatment

may be necessary prior to discharge (to a sewer system or navigable waterway). Several skid mounted treatment systems are commercially available.

3.10. **Design Procedures for Passive Collection Systems**

3.10.1. *General.* The purpose of a passive gas collection system is to prevent the build-up of gas pressure within the landfill to maintain the stability of the landfill cover and to prevent the off-site migration of landfill gas. Passive collection systems can be designed as blankets, wells, or trenches. Strict design procedures are often not employed to design passive systems because they are typically placed on old and/or small landfills where the potential for landfill gas generation is small. Instead of using strict design procedures, rules of thumb are commonly applied in the design of passive gas collection systems.

3.10.2. *Passive Blanket Collection Systems.* Because blanket gas collection systems do not penetrate down into the waste layer, they are less effective than well systems in preventing the off-site migration of landfill gas. However, blanket gas collection systems are effective at preventing the buildup of pressure beneath a cover system. Granular soil layers used as gas collection blankets are typically 305 mm (12 inches) in thickness. If a geonet drainage layer is used it will typically be a geocomposite with a geotextile attached to one or both sides of the geonet. The geotextiles attached to the geonet prevent soil and waste from entering the geonet. The geotextiles also increase the frictional resistance at the drainage layer interfaces. Geotextiles can also be used as the gas collection layer if the anticipated production of LFG is very small and the normal stresses acting on the geotextile are small. Thiel (1998) recently reported air transmissivity values for geotextiles. The following are the average flux values reported:

Geotextile Type	Transmissivity
540 g/m^2 (16 oz/yd^2)	
Wet	9.74×10^{-7} m^3/s/m
Dry	6.50×10^{-6} m^3/s/m
680 g/m^2 (24 oz/yd^2)	
Wet	2.81×10^{-6} m^3/s/m
Dry	1.87×10^{-6} m^3/s/m

3.10.2.1. *Design Procedures for Passive Blanket Collection Systems.* If there is a potential for the build-up of gas pressure beneath a geomembrane barrier layer, slope stability becomes a concern and a more rigorous design procedure should be implemented. The general steps required when considering gas pressure in the design of a passive landfill gas collection blanket are as follows:

- Estimate the maximum gas flux that needs to be removed from below the landfill cover.

- Perform slope stability analyses to estimate the gas pressure at which slope instability will result.
- Design a vent system below the cover that will evacuate the assumed gas flux and prevent the build-up of gas pressure beneath the geomembrane.

If the gas-collection layer is a granular material, it is reasonable to assume that the granular material will be holding a certain amount of capillary water either due to rain during construction, or from condensate collecting beneath the barrier layer. The reduction in gas permeability due to partial saturation of the layer can be estimated using the Brooks and Corey relationship. Based on preliminary experimentation, Thiel (1998) makes the following recommendations on the field-gas permeability of granular collection layers:

- For fine sands containing less than 10–15 percent fines, the field-gas permeability can be taken as the dry-gas permeability reduced by a factor of 5 to 10 to account for the presence of field-moisture.
- For clean medium and coarse sands, the field-gas permeability can be taken as the dry-gas permeability reduced by a factor of 2 to account for the presence of field-moisture.
- For rock gas collection layers, there will be little or no measurable reduction in permeability due to water retained within the pore spaces of the rock.

Calculations and experimental evidence from the literature suggest that landfill gas flow rates in passive blanket collection layers are generally expected to be laminar and Darcy's law applies.

   3.10.2.2. *Maximum Acceptable Gas Pressure.* Thiel (1998) outlines a design methodology for estimating the slope stability for the case where landfill gas pressure builds up beneath the barrier layer. The following equation can be used to estimate the maximum acceptable gas pressure beneath the geomembrane barrier layer:

   Factor of Safety = $[(H\gamma \cos B - \mu_g) \tan \phi] / H\gamma \sin B$

where:

   H = height of cover soil (m)
   γ = cover soil density (kN/m^3)
   μ_g = landfill gas pressure (kPa)
   B = slope angle.

   3.10.3. *Design Considerations for Passive Well Collection Systems.* Passive gas collection wells are typically spaced approximately 60 meters (200 feet) apart, i.e.: 1 per 0.4 hectare (1 per acre). Additional wells will be required if perimeter monitoring probes indicate the methane concentration exceeds the regulatory limit for the site. Vertical risers should also be located at high points in the collection system within the landfill.

3.11. **Design Procedures for Active Well Collection Systems**

3.11.1. *General.* Spacing of LFG collection wells for active systems is highly dependent on site-specific variables such as waste density, waste moisture content, waste thickness, well design, and cap configuration. The following methods have been used to determine the well spacing of LFG collection systems:

- Cylinder method. This is a popular approach used by numerous consulting firms and involves estimating the amount of landfill gas being produced within the radius of influence (ROI) of an extraction well.
- Field pump tests. The designer uses pump test results to obtain data to identify the site-specific zone of influence of extraction wells.
- Prescriptive/regulatory criteria. Some states have regulatory requirements related to gas vent spacing. For example, the Wisconsin Department of Natural Resources requires all designs to use a maximum of 150-foot radius of influence unless a pump test is conducted.
- Rule of thumb criteria. This method relies on past experience to aid in the layout of the gas collection wells. Some designers correlate gas vent well spacing to the depth of the waste. Typically, wells are spaced no farther apart than 3 times the depth of the waste with a maximum acceptable spacing of 300 feet.

Whichever design method is used, the designer must ensure gas is collected from the entire area of the landfill and off-site migration is prevented.

3.11.1.1. *Cylinder Method.* This approach assumes all gas generated from within a cylinder of a specified radius is removed by the well and that no leakage from the atmosphere enters the landfill (Emcon, 1980). This method is most appropriate for landfills with low-permeability covers. Figure 3.11 shows a typical layout for wells designed using the cylinder method. The following equations can be used to apply the cylinder method:

3.11.1.1.1. *Flow Rate for Entire Landfill.* The following equation can be used to estimate the total amount of gas being generated from within a landfill:

$Q_{tot} = (V)(D)(G)/(\text{percent methane in gas})$

where:

V = volume of waste
D = density of waste
G = methane production rate.

Typically, methane represents approximately 30 to 55 percent of the total volume of gas generated from a landfill. Since the G term is only an estimate of the amount of methane generated, to determine the total landfill gas flow rate, divide $(V)(D)(G)$ by the percent methane.

3.11.1.1.2. *Determine Flow Rates from Each Well (Cylinder Method).* The flow rate from individual wells can be determined by assuming a radius of influence and estimating the amount of gas generated from within this radius using the methane production rate discussed above:

$$Q = \pi (R^2 - r^2) (t)(D)(G)/(\% \text{ methane})$$

where:

Q = methane flow rate
R = radius of influence
r = borehole radius
t = waste thickness
D = density of waste
G = methane production rate.

As a rough approximation, the total flow from all wells as determined by the cylinder method, must be greater than or equal to Q_{tot} (Calculated above).

ΣQ from each well $\geq Q_{tot}$

3.11.1.1.3. *Determine pressure drop required at each well to maintain assumed radius of influence.* The following equation is used to estimate the vacuum required to prevent the build-up of pressure within the landfill due to the generation of landfill gas:

$$\Delta P = \mu G_{tot} D \left[R^2 \ln(R/r) + (r^2/2) - (R^2/2) \right] / 2 K_s$$

where:

ΔP = pressure difference from the radius of influence to the gas vent
R = radius of influence
r = radius of borehole
μ = absolute viscosity of the landfill gas
K_s = apparent permeability of the refuse
D = density of the refuse
G_{tot} = Total landfill gas production rate = G/(% methane)

In order to ensure that landfill gases generated within the landfill do not escape through the subsurface or through the cover, the vacuum used during full-scale operations will often be somewhat greater than the value calculated above. The required vacuum is often based on data

collected from gas monitoring probes located at the perimeter of the landfill. These perimeter wells are typically monitored for vacuum and methane content.
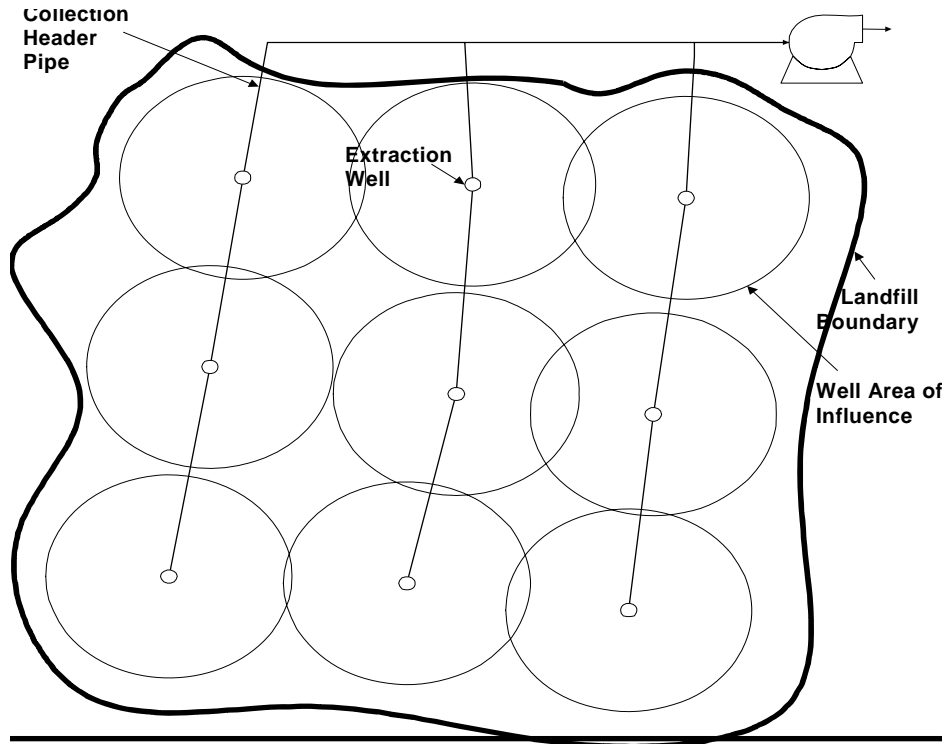
Figure 3.11. Typical Extraction Well Layout.

3.11.1.2. *Landfill Gas Generation Rate.* The equation shown in the previous paragraph requires the input of a gas generation rate. Methods to estimate the rate of methane generation were discussed in Chapter 2 of this EM. Estimates of methane gas generation rates have also been reported by numerous authors. Table 3.1 is a summary of reported values. It should be noted that the values reported in the table are representative of MSW landfills during their most active periods of gas production. Gas generation rates will decline as the waste ages. It should also be noted that methane is only one component of the gas being generated by a landfill. To conservatively estimate total gas production the values shown in Table 3.1 should be doubled.

Table 3.1.
Landfill Gas Generation

Methane Gas Generation Rate m^3/(kg*day)	Reference
3.29 to 20.1 × 10^{-6}	Bagchi, Amalendu, (1990). "Design, Construction, and Monitoring of Sanitary Landfills," John Wiley, New York
3.52 to 21.1 × 10^{-6}	Stecker, Phillip, (1989). "Active Landfill Gas Recovery Systems," University of Wisconsin Sanitary Landfill Leachate and Gas Management Seminar, Madison, WI, December 4-7.
3.56 to 20.5 × 10^{-6}	Emcon Associates (1980). "Methane Generation and Recovery from Landfills," Ann Arbor Science, Ann Arbor, Michigan
1.76 to 5.28 × 10^{-6}	Farquhar, Grahame J., (1989). "Factors Influencing Landfill Gas Recovery," University of Wisconsin Sanitary Landfill Leachate and Gas Management Seminar, Madison, WI, December 4-7.
1.76 to 7.04 × 10^{-6}	Ham, Robert K., (1989). "Landfill Gas Generation: Compositions, Quantities, Field Test Procedures and Uncertainty," University of Wisconsin Sanitary Landfill Leachate and Gas Management Seminar, Madison, WI, December 4-7.
27.4 to 54.8 × 10^{-6}	Ham, Robert K., Barlaz, Morton A., (1987). "Measurement and Prediction of Landfill Gas Quality and Quantity," ISWA International Symposium, "Process, Technology and Environmental Impact of Sanitary Landfills," Cagliari, Sardinia, Italy, October 20-23.
13.7 to 21.9 × 10^{-6}	Pohland, Frederick G., Harper, Stephen R. (1986), "Critical Review and Summary of Leachate and Gas Production from Landfills," EPA/600/2-86/073. USEPA, Cincinnati, OH.

3.11.2. *Other Design Considerations.* The maximum gas extraction rate from any well is limited by the available vacuum and air intrusion into the waste (i.e., overpull). Overpull can result in oxygen being pulled into the landfill and killing the methane producing bacteria or causing landfill fires. Additional items to keep in mind when establishing spacing of LFG wells:

- Shallower LFG wells have a smaller zone of influence.
- Extraction systems, whose primary purpose is migration control, should have a closer well spacing near the perimeter to minimize the potential for off-site migration.
- Access to proposed well locations by drill rigs must be considered when laying out the gas collection system.
- Disposal of drill rig waste.

CHAPTER 4
Design of Landfill Off-Gas Treatment Systems

4.1**. Introduction.** A blower/flare station is typically composed of the following components:

- Structure.
- Blower.
- Flare.
- Flame Arrestor.
- Flow Metering.
- Piping and Valves.
- Electrical controls.

4.2. **Structure.** The blower/flare station should be located on native soil and should be accessible by vehicles to allow for flare and blower maintenance. In inclement climates, all the basic equipment except the flare should be located within an enclosed structure. It should be noted that an enclosed blower/flare structure is classified as a Class I, Division I, and Group D Hazardous Location as defined by the National Electric Code. Therefore, all equipment housed in the building must be rated for this classification. In mild climates, the equipment does not have to be located within an enclosed structure. For most sites, a security fence should surround the flare station. Within the station, there should be ample access to units for maintenance activities and replacement.

4.3. **Blower**. The blower must be able to function under a range of conditions that may result due to changes in LFG composition and flow rate. The blower applies the required vacuum on the LFG collection system and supplies the required discharge pressure for the flare. The amount of vacuum required depends on the size of the LFG collection system and typically varies from 40 to 60 inches (1.02 and 1.52 meters) of water column. The amount of pressure required is governed by the flare burner configuration and typically varies from 10 to 20 inches (0.25 to 0.51 meters) of water column. LFG collection systems generally use centrifugal or positive displacement type blowers:

4.3.1. *Centrifugal Blowers.* These blowers are typically employed for applications requiring less than 203.2 cm (80 inches) of water vacuum. Centrifugal blowers are compact and produce an oil-free airflow. The principle of operation is as follows: A multistage impeller creates pressure through the use of centrifugal force. A unit of air enters the impeller and fills the space between two of the rotating vanes. The air is thrust outward toward the casing but then is turned back to another area of the rotating impeller. This process continues regenerating the pressure many times until the air reaches the outlet.

4.3.2. *Rotary Lobe Blowers.* These positive displacement blowers are typically used for a medium range of vacuum levels (roughly 50 to 460 cm (20 to 180 inches) of water vacuum). During operation of these blowers, a pair of matched impellers rotates in opposite directions, trap a volume of gas at the inlet, and move it around the perimeter to the outlet. Timing gears that are keyed into

the shaft synchronize rotation of the impellers. Oil seals are required to avoid contaminating the air stream with lubricating oil. These seals must be chemically compatible with the site contaminants. When a belt drive is employed, blower speed may be regulated by changing the diameter of one or both sheaves or by using a variable speed motor.

    4.3.3. *Blower Summary.* Centrifugal blowers are more commonly used due to their greater flexibility in adjusting to variable flow rates and lower long-term maintenance costs. Centrifugal blowers also result in power consumption savings when the flow rate is reduced due to the proportional decrease in horsepower. A comparison of centrifugal and positive displacement blowers is shown in the Table 4.1.

Table 4.1.
Blower Type Comparison.

Centrifugal	Positive Displacement
Lower long-term maintenance	Higher long-term maintenance
Direct driven (Generally)	Belt driven
Ample tolerances, little wear and tear of internal parts	Close tolerance of internal parts, more wear and tear. SAFETY NOTE: As parts wear, there is a possibility of metal to metal contact which could produce a spark with enough energy to ignite a flammable atmosphere.
Bearings mounted outboard of blower housing, no chance that discharged gas will be contaminated	Internally lubricated, more chance that discharged gas will be contaminated
Can deliver variable volume at constant speed	Delivers constant volume at constant speed
Less power used for lower flows	No power savings for lower flows, vent excess flows unless you change the speed at which the blower rotates through change in sheave size or use a VFD motor
Deliver relatively constant pressure at constant speed	Deliver variable pressure at constant speed
Less noise, easier to muffle	More noise, difficult to silence
Since horsepower is in direct proportion to flow, ammeter with volumetric scale can be used to approximate flow	Measurement of flow with an ammeter is not reliable, more expensive meter may be required
Produces a smooth, non-pulsating flow when operating at any point beyond the surge range	Produces a pulsating flow beyond the surge range

4.3.3.1. Since LFG may contain particulates and aqueous vapor that may be corrosive, a protective coating should be applied to all blower parts in contact with the gas. Flexible connections are recommended on both inlet and outlet sides of a blower to adsorb vibrations during operation. In addition, the blower motor should be explosion-proof and suitable for Class I, Division I, Group D, and Hazardous Locations. Both a temperature and pressure gage should be included on each side of the blower. These instruments aid in operating the blowers within the manufacturer's recommendations as well as the system at the desired flow rate.

4.3.3.2. Depending on the potential health hazards due to mechanical failure, a back-up blower is sometimes provided in the event the primary unit fails or is out of service for maintenance. In addition, design redundancy provides greater operating flexibility. Stand-by units not in service should be isolated from the LFG flow stream by butterfly or gate valves. These valves, when closed, will prevent accumulation of condensate from the LFG in the piping and blower casing. The valves can also be used to adjust the flow rate and allow removal of the unit for maintenance.

4.4. **LFG Energy Recovery Systems**. In large municipal landfills, LFG is being developed as an energy resource. Generally, the collection of gas for energy recovery purposes has been limited to large landfills with over 1 million tons of solid waste in place. Military landfills are typically smaller in size and often do not contain waste types conducive to the production of large enough quantities of methane to be economically recovered for use as an energy source. Energy recovery options are briefly discussed for the reader's information. The following four approaches have been used for LFG energy recovery:

- Fuel a gas turbine engine
- Generate electricity by the operation of a gas turbine or an internal combustion engine
- Fuel a boiler. Steam generated could drive a turbine/generator set up to produce electricity
- Upgrade the gas to pipeline quality for delivery to a utility distribution system.

Typical LFG contains approximately 500 Btu per standard cubic foot (4,450 K cal/m^3) of energy whereas pipeline-quality gas contains 1,000 Btu/scf (8,900 K cal/m^3). The energy content of LFG varies widely depending upon the performance of the gas collection system and the stage of decomposition within the landfill. Active extraction systems that draw excessive amounts of atmospheric air into the subsurface can also result in dilute influent gas streams.

4.5. **Flares.** Two types of flare systems are generally used for LFG off-gas collection and treatment systems: open-flame flares and enclosed flares. Each flare type has advantages and disadvantages. Both types of flares have been used for LFG treatment.

4.5.1. *Open-Flame Flare.* An open-flame flare or candle-stick flare represents the first generation of flares. The open-flame flare was mainly used for safe disposal of combustible gas when air emission control was not a high priority. Open-flame flare design and the conditions

- Simple design since combustion control is not possible.
- Ease of construction.
- Most cost-effective way of safely disposing of landfill gases.
- Open-flame flares can be located at ground level or elevated.

The major disadvantages of open-flame flares are:

- They do not have the flexibility to allow temperature control, air control, or sampling of combustion products due to its basic design.
- Sampling off-gas from open-flame flares is difficult. Sample probes placed too close to the flame will measure high CO_2 and hydrocarbon levels. Samples taken further away from the flame are diluted unpredictably by air.

4.5.2. *Enclosed Flares.* Enclosed flares differ from open flares in that both LFG and airflows are controlled. While a blower pushes LFG through the flame arrestor and burner tips, the flare stack pulls or drafts air through dampers and around burner tips. The stack acts as a chimney, so its height and diameter are critical in developing sufficient draft and residence time for efficient operation. Enclosed flares are more commonly used than open flares in LFG applications for two reasons:

- They provide a simple means of hiding the flame (i.e., neighbor friendly).
- Periodic sampling of these flares can be conducted to ensure the required rate of emissions reduction is being achieved.

A typical schematic of an enclosed flare system is shown in Figure 4.1. An enclosed flare burns LFG in a controlled environment to destroy harmful constituents. The basic flare unit consists of a multi-orifice burner and burner chamber enclosed in a stack containing refractory insulation. Usually the stack height is greater than the flame height so the flame is not visible to the public. The typical stack height is 20 to 30 feet. Exit gas temperature is measured by thermocouple and is recorded at the flare control panel. An automatic combustion air control system (dampers) operates based on the temperature controller. The dampers provide ambient air to the flare interior for combustion oxygen and for controlling the exit gas temperature. Sampling ports are located in the walls near the top of the stack where emissions monitoring are performed. A built-in staircase and platform is usually provided for access to the sampling areas. A flare will include an electric pilot ignition system. The pilot ignition system requires auxiliary fuel; therefore, a small propane tank must be located near the flare to serve as pilot fuel.
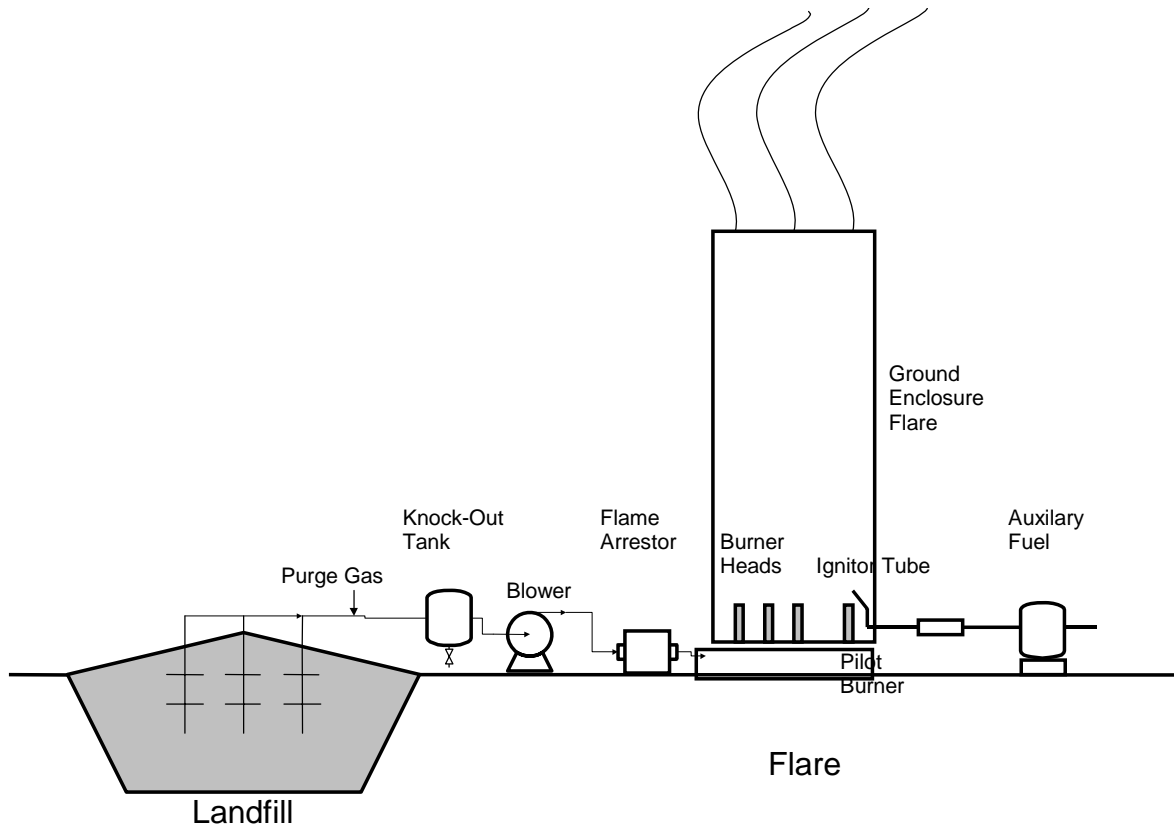
Figure 4.1. Enclosed Flare Schematic.

4.5.3. *Flare Design Criteria.* The basic flare unit consists of the following components:

- Multi-orifice burner
- Burner chamber.
- Automatic combustion air control system (dampers).
- Electric pilot ignition system.
- Sampling ports.
- Flare control panel.
- Temperature controller (flare stack high temperature interlock).
- Flame arrestor.
- Emission control.

4.5.3.1. The elements of combustion that must be addressed in the design of a LFG flare are:

- Residence time.
- Operating temperature.

- Turbulence.
- Oxygen concentration.

4.5.3.2.   These elements are interrelated and, to some extent, dependent on each other. Adequate time must be available for complete combustion. The temperature must be high enough to ignite the gas and allow combustion of the mixture of fuel and O_2. The residence time in a combustor must be sufficient for hydrocarbons to react with the O_2. Residence times for VOCs can vary from 0.25 to 2.0 seconds. Solid particles, such as carbon, may require as long as 5 seconds for complete destruction.

4.5.3.3.   The operating temperature of a combustion unit depends upon the material to be combusted. The temperature should be about 148 to 260°C (300 to 500°F) above the auto-ignition temperature of the LFG. CH_4 auto ignites at 540-760°C (1000-1400°F), thus a minimum operating temperature of 760°C (1400°F) is often specified. A temperature that is too high may cause refractory insulation damage as well as production of excess NO_x, while a temperature that is too low may result in the production of excess carbon monoxide and unburned hydrocarbons. Flare Stack high and low temperature alarms should be provided as well as a high-high interlock to shutdown the gas supply to the flare stack in the event of an excessively high temperature. Methane has a flame temperature of 1880° C (3416° F) when no excess air is present to cool the gas.

4.5.3.4.   There must be enough turbulence to mix the fuel and O_2, and enough O_2 to support combustion. Mixing the LFG and air at the burner tip is critical to proper operation of the flare. Proper mixing and adequate turbulence will create a uniform mix of LFG and air in the combustion zone, whereas improper mixing will result in flue gas stratification, which contributes to high emissions and unstable operation.

4.5.3.5.   Operating at high flow rates and tip velocities requires flame stabilizers to prevent the flame from extinguishing itself. Windshields allow the flame to establish itself and resist high wind conditions.   Automatic pilots sense the LFG flame and automatically relight the flare when necessary.

4.5.3.6. A gas flow meter system is necessary to measure LFG flow to the flare. The gas flow should indicate both current flow and accumulated flow. For data storage, it is recommended that digital storage be used instead of paper recorder to avoid maintenance problems.   The total volumetric flow rate to the flame must be carefully controlled to prevent flashback problems and to avoid flame instability. A gas barrier or a stack seal is sometimes used just below the flare head to impede the flow of air into the flare gas network.

4.5.3.7.   Thermocouples are used to monitor the flame in open and elevated flares. For enclosed flares, ultraviolet (UV)-type flame detectors should be used. The UV flame detectors can detect instantaneous flame failure so the inlet valve can be shut before the vessel fills up with unburned gas.

4.5.4. *Flare Operating Criteria.* The design and selection of landfill flares depends upon the required design and operating objectives. In any case, flares should be designed and manufactured to provide the minimum operating temperature under a range of LFG compositions and flow rates. Other typical flare operating criteria include the following:

- Reactive Organic Gas (ROG).
- Exit Gas Temperature.
- Nitrogen Oxides (NO_x).
- Residence Time.
- Sulfur Oxides (SO_x).
- Carbon Monoxide (CO).
- PM10 (Particulate Matter of Aerodynamic diameter smaller than or equal to a nominal 10 microns).

4.6. **Condensate Collection Equipment.** Landfill gas is typically saturated with water vapor. As the gas cools in the extraction system piping, the vapor condenses into droplets that eventually combine into LFG condensate. Accumulations of condensate in LFG pipelines can obstruct the flow of gas. Therefore, LFG condensate must be removed in a controlled manner. Condensate control is required irrespective of how great a vacuum is imposed on the collection system. Knock-out tanks are normally used to remove condensate from gas entering the flare station. Low points in collector piping should have barometric drip legs installed and multiple arrays of piping should meet at common condensate knock-out tanks. Environmental regulations often require the treatment of collected condensate.

4.7. **Auxiliary Fuel.** Auxiliary fuel is required if the LFG methane content is too low to burn by itself. The operating temperature is a function of gas composition and flow rate. Unfortunately, LFG composition and flow rate are variable and somewhat unpredictable. LFG typically produces a maximum of 500 BTUs per cubic foot when it contains 50 percent methane. Natural gas produces approximately 1033 BTU per cubic foot. Fortunately, flares are manufactured which are able to provide the minimum operating temperature under a range of LFG compositions and flow rates. However, when the BTU loading derived from LFG is outside the flare design range, auxiliary fuel is required at the flare.

4.8. **Flame Arrestor.** Another important unit independent from the flare is the flame arrestor that is installed in the LFG inlet line. The function of the flame arrestor is to prevent the propagation of flame into the header pipes. The flame arrestor is packed with a flame quenching media that is durable, resistant to oxidation, and easy to clean. Pressure gauges and sampling ports must be installed on each side of the flame arrestor to indicate the degree of clogging and whether removal for cleaning is required. Proper sealing of the flame arrestor in the housing is essential. Since a flame arrestor requires periodic factory cleaning, a stand-by flame arrestor should be kept on-site for use during maintenance activities. Also, in selecting a flame arrestor, an easily removable design

should be used to facilitate cleaning and inspection. The flame arrestor housing is generally carbon or stainless steel.

4.9. **Flow Metering.** An important additional piece of equipment at a blower/flare station is a gas flow metering system. LFG flow rate information is the basis for controlling operation of the extraction and treatment system. The gas flow meter should display current and total gas flow.

4.10. **Piping and Valves.** Cast iron or ductile iron materials are recommended. Flanged piping, valves, and fittings are also recommended. Hand-operated, wafer style butterfly valves are easiest to install and use for blower adjustments.

4.11. **Electrical Design Requirements**

4.11.1. *General.* The electrical system planning and design should consider materials, equipment, and installation of all electrical components. A detailed discussion electrical system planning is presented in EM 1110-1-4001. The following paragraphs outline some of the electrical control requirements unique to landfill gas flare systems.

4.11.2. *Electric Controls.* Necessary blower controls include:

- MANUAL/AUTO/OFF selector switch.
- Failure light.
- Time elapse meter.
- Motor ON/OFF light.

Normally, the blower is operated in AUTO mode that enables the blower to be automatically controlled from the control panel. The blower MANUAL operation is used only during testing. A time elapse meter is typically used to indicate blower operation duration and help establish the blower maintenance period. Electrical controls included on the flare control panel are:

- MANUAL/AUTO/OFF selector switch.
- Temperature controller.
- Pilot ON/OFF light.
- Temperature recorder.
- LFG ON/OFF light.
- Aux fuel ON/OFF light.
- Flame failure light.

Normally, the flare is operated in AUTO mode and requires an operator to push the start button to initiate flare ignition and blower operation.

4.12. **Automation of Controls.** A good instrumentation and control system design will assure that the individual components of the off-gas collection and control system are coordinated and operate effectively. This paragraph will present:

- Control elements
- Degree of automation
- Special instrumentation requirements.

4.12.1. *Control Elements.* At a minimum, the following process control components are required:

- Pressure and flow indicators for each well
- Blower motor thermal overload protection
- Vacuum relief valve or vacuum switch to effect blower shutdown
- Pressure indicators at blower inlet and outlet
- High-level switch/alarm for condensate collection system.

A typical piping and instrumentation diagram (P&ID) is shown in Figure 4.2.
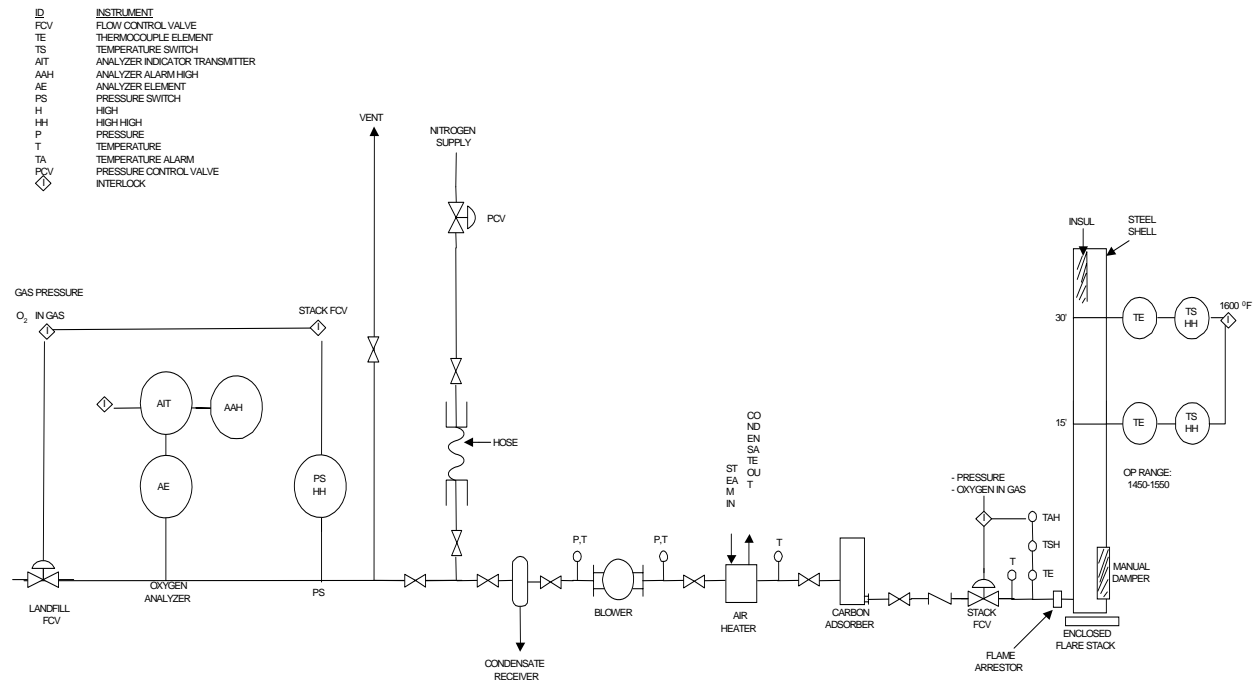
Figure 4.2. Typical Piping and Instrumentation Diagram (P&ID) for a Blower/Enclosed Flare Station.

4.12.1.1. *Gas Pressure Gauges.* Pressure gauges in the operating range of the gas management system are readily available commercially. Several types are available. The only design consideration beyond the pressure range is corrosion resistance to the compounds present in the landfill.

4.12.1.2. *Methane Gas Detectors.* Gas detectors may be placed in the feed manifold system of active collection systems to monitor the explosive range (or BTU content) of the recovered gas. Systems that burn the gas have different operating target values than systems that vent or otherwise dispose of the gas. Methane concentration data can be used to adjust landfill gas extraction and processing conditions. Infrared instruments that measure methane gas concentration in the manifold system may also be used.

4.12.1.3. *Alarms.* The gas control system will usually require several alarms to ensure safe and efficient operation. Alarms must be provided to ensure the condensate collection system does not overflow into the blower train. Alarms are required to alert for too rich or too lean a feed stream for combustion systems. Some blowers and vacuum pumps require alarms for overpressure or excessive vacuum in parts of the piping system. The system may also contain flow rate alarms to indicate too much or too little gas movement.

Some degree of alarm protection is provided in the electrical system that serves the blowers or pumps in the form of thermal overload systems, circuit breakers, or fuses.

4.12.1.4. *Control Panel Layout.* Scale drawings of the control panel should be prepared for all electrical components and associated wiring. Depending on the project, control drawings may be submitted as a shop drawing by the instrumentation and control contractor.

4.12.1.5. *Logic Diagram.* A logic diagram must be included if the process control logic is not apparent from the P&ID. This diagram shows the logical relationships between control components. For example, the diagram may show that if a particular switch is placed in the "on position" and there are no alarm conditions, then the blower will turn on and activate a green indicator light. Another example is when the alarm switch is placed in the on position, signaling that if the LFG is too rich, then the blower will be turned off to prevent explosive conditions in the flare.

4.12.2. *Degree of Automation.* The degree of automation is generally dependent on the complexity of the off-gas treatment system, the remoteness of the site, and monitoring and control requirements. Typically, there is a trade-off between the initial capital cost of instrumentation and control equipment, and the labor cost savings in system operation.

Systems designed for unattended operation would incorporate the greatest degree of automation of system controls. Control schemes may include the use of remotely located PLC, remote data acquisition, and modems and radio telemetry. System mechanical and electrical components would

be selected on the basis of having optimum reliability while requiring minimum maintenance and adjustment.

There are three forms of process control: local, centralized, and remote. In a local control system, all control elements (i.e., indicators, switches, relays, motor starters, etc.) are located adjacent to the associated equipment. In a centralized control system, the control elements are mounted in a single location. These systems may include a hard-wired control panel, a programmable logic controller (PLC), or a computer. Remote control can be accomplished several ways including the use of modems or radio telemetry. To select the appropriate control scheme, the advantages and disadvantages of each control scheme must be considered. A localized control system is less complex, less expensive, and easier to construct. Centralized control systems are easier to operate. Automated process control is a complex topic that is beyond the scope of this document; however, several points are worth considering. Often plant operators will be more familiar with traditional hard-wired control logic than with control logic contained in software. However, process logic contained in software is easier to change (once the operator learns the software) than hard wiring.

4.12.3. *Special Instrumentation Requirements.* Additional information on instrumentation requirements can be found on the Technology Transfer Network. The Technology Transfer Network is a collection of technical Web sites containing information about many areas of air pollution science, technology, regulation, measurement, and prevention. The Emission Measurement Center (EMC) provides access to emission test methods and testing information for the development and enforcement of national, state, and local emission prevention and control programs. The EMC web site can be found at the following address: http://www.epa.gov/ttn/emc/.

4.13. **Other Design Considerations.**

4.13.1. *Site Working Areas.* Areas should be designated on the site plan for temporary storage. Access to the landfill should be provided to check pipe headers, wellheads, condensate traps, and sumps.

4.13.2. *Utilities.* Large landfills will need electricity, water, communication, and sanitary services. Remote sites may have to extend existing service or use acceptable substitutes. Portable chemical toilets can be used to avoid the high cost of extending sewer lines; potable water may be trucked in; and an electric generator may be used instead of having power lines run into the site.

4.13.3. *Emergency Power.* Many LFG extraction systems are equipped with emergency power sources such as generators to keep the blowers operating continuously. Generators should be designed to automatically turn on if the normal power supply fails.

4.13.4. *Water.* Water is sometimes required for cooling and sanitary use. A water supply may also be required for fire protection of buildings and or equipment.

4.13.5. *Fencing.* At some sites, it is desirable to construct perimeter fences to keep out trespassers and animals. If vandalism and trespassing are to be discouraged, a 1.8-m (6-foot) high chain link fence topped by 3 strands of barbed wire is desirable. A wood fence or a hedge may be used to screen site operations from public view.

4.13.6. *Lighting.* If the landfill has structures (employee facilities, administrative office, equipment repair, or storage sheds, etc.) interior lighting requirements need to be determined. Permanent security lighting may also be desirable in some situations. Refer to EM 385-1-1, Section 7 for lighting requirements.

4.13.7. *Labor Requirements.* LFG recovery systems typically do not require extensive labor commitments. A regular O&M schedule should be implemented to ensure the proper and uninterrupted operation of the system. Depending on the LFG control system installed and the size of the facility, one full-time operator may be needed to operate and maintain the gas collection system during the day. An automatic control system is designed to operate and control the system at night. Flare stations are often left unattended. In this case, a computer monitoring and control system will shut down the collection system and notify operators via an auto dialer in case of malfunction.

4.13.8. *System Safety.* Due to the explosive nature of landfill gas, flare station electrical equipment and fixtures should typically be classified accordance with 29 CFR 1910 Subpart S or NEC as Class 1, Division 2, Group D, or which ever is more stringent. Some local codes may be more restrictive than the aforementioned and should be examined before design.

**CHAPTER 5
Operation and Maintenance**

5.1. **Introduction.** An operation and maintenance plan for a landfill gas collection system must be prepared that addresses the following:

- Extraction wells.
- Gas monitoring probes.
- Condensate collection and treatment.
- Flare station.

A site-specific monitoring program should be established that is flexible and performance based. Landfill gas 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 operation and maintenance of landfill gas collection systems can be found in the reference entitled "Landfill Gas Operation and Maintenance Manual of Practice."

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 gas extraction wells. The following lists the components of air:

- Nitrogen N_2 78.084%
- Oxygen O_2 20.947%
- Argon Ar 0.934%
- Carbon Dioxide CO_2 0.033%
- Neon Ne 18.2 parts per million
- Helium He 5.2 parts per million
- Krypton Kr 1.1 parts per million
- Sulfur dioxide SO_2 1.0 parts per million
- Methane CH_4 2.0 parts per million
- Hydrogen H_2 0.5 parts per million
- Nitrous Oxide N_2O 0.5 parts per million
- Xenon Xe 0.09 parts per million
- Ozone O_3 0.07 parts per million
- Nitrogen dioxide NO_2 0.02 parts per million
- Iodine I_2 0.01 parts per million
- Carbon monoxide CO trace

- Ammonia NH_3 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 gas composition, vacuum, flow, and gas temperature. The monitoring should be more frequent if the gas is used as fuel in an energy recovery project. Gas composition measurements may include percentages of methane, carbon dioxide, oxygen, nitrogen and contaminant/balance gases. If excessive vacuum is applied to a gas well, 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 air intrusion at extraction wells is to check the concentration of nitrogen. Any amount of nitrogen gas in a well is a sign of air intrusion. Unfortunately, monitoring for nitrogen gas requires analysis by a gas chromatograph, which is time consuming and expensive. The presence of oxygen is also an indicator of 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 air intrusion.

5.2.3. *Balancing Techniques.* Techniques for balancing a group of LFG extraction wells include the following.

5.2.3.1. *Valve Position.* Valve position gives a very rough indication of flow rate.

5.2.3.2. *Wellhead Vacuum.* Wellhead vacuum can provide a very rough estimate of radius of influence and flow rate.

5.2.3.3. *Gas Flow Rate.* Gas 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 is generally determined empirically based on gas composition readings.

5.2.3.4. *Gas 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 if the gas temperature begins to rise.

5.2.3.5. *Gas Temperature.* Rising gas temperature measured at a well is another sign of air intrusion. Typically, gas temperatures greater than 55° C (131° F) indicate some air intrusion is occurring in the waste and the flow rate should be reduced.

5.2.3.6. *Summary.* The best way to balance an individual landfill gas extraction well is by monitoring some or all of the parameters listed above, plotting trends over several monitoring events and reviewing the trends to pick the setting that meets the goals of your extraction system.

5.2.4. *Primary Well Field Monitoring.* Primary wells are those wells located within the landfill boundaries. The frequency of landfill gas 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 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 gas. Perimeter systems extract poor quality LFG that is often high in oxygen due to 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 gas before it escapes from the landfill. The frequency of monitoring is based on the perceived threat to the public from the off-site migration of gas. 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.

5.2.6. *Barometric Pressure.* The amount of gas escaping from a landfill surface changes as atmospheric pressure varies, even when the gas production rate is constant. Methane concentrations and landfill gas 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 clogged with leachate is suggested (Michels 1998):

- Discontinue gas extraction.
- 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.
- If leachate continues to flow into the well or it takes more than five days to remove all the liquid, then a permanent method of leachate collection is probably required.

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

- One well casing for LFG extraction and leachate extraction
- LFG extraction wellhead installed at the top of the well casing
- Pneumatic or electric pump installed in the well casing (pneumatic pumps are most common due to the explosive environment)
- Discharge 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 air intrusion into the landfill which will minimize aerobic activity. Atmospheric air is 21% oxygen and 79% nitrogen. Gas composition typically is measured with a portable gas analyzer. The readings will be in percent methane, carbon dioxide, and oxygen. The balance is assumed to be nitrogen. The nitrogen-to-oxygen ratio for atmospheric air is $79/21 = 3.76$. Gas extraction wells are monitored in order to evaluate system performance. If the oxygen content reaches 3.2% or the nitrogen content is 12% ($3.2 \times 3.76 = 12$ %) sufficient air intrusion may be occurring to start 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:

- Oxygen content is increasing and exceeds 3.2 percent by volume.
- Nitrogen content is increasing and exceeds 12 percent.
- Gas temperature is increasing and exceeds $60^{o}C$ ($140^{o}F$).

The following parameters are evidence of fire within the landfill:

- Gas temperature exceeds $75^{o}C$ ($167^{o}F$).
- Rapid settlement of the cover system.
- Carbon monoxide levels are greater than 1000 ppm.
- Combustion residue is present in the LFG Lines.

Landfill fires can be prevented by:

- Decreasing the extraction rate which will decrease air intrusion.
- Preventing air intrusion by decreasing the air permeability of the landfill cover.
- Increasing the monitoring frequency of the extraction wells and probes.

If a fire occurs, fire control may be accomplished through the injection of nitrogen or CO_2 into the landfill to suffocate the fire. Extraction of landfill gas should also be terminated to prevent oxygen from being drawn into the landfill (Israel 2000).

5.2.9. *Vertical Profiling.* A perimeter gas extraction well will typically penetrate several geologic layers with each layer exhibiting different properties. Landfill gas 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 landfill gases are traveling through. The profiling involves using a probe to take continuous gas samples and measuring the gas 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 landfill gas.

5.2.10. *Inspection and Maintenance.* Inspection and maintenance should be performed during each sampling event. Each gas 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 they occur. 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. **Gas Monitoring Probes.**

5.3.1. *Monitoring Procedures.* The reference entitled "Landfill Gas Operation and Maintenance Manual of Practice" provides excellent information on monitoring landfill gas perimeter probes and interpretation of the collected data. Monitoring probes are typically placed outside the waste mass and are normally located at the property boundary or the point of regulatory compliance. Gas monitoring probes are typically tested for the following parameters:

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

5.3.1.2. *Gas Concentrations.* Leak check the entire sample train. Purge the probe of two volumes of gas and then record the appropriate gas concentrations (methane, carbon dioxide, oxygen, nitrogen, hydrogen sulfide, etc.).

5.3.1.3**.** *Water 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 monitored during a sampling

event. As mentioned previously, landfill gas is a collection of air pollutants including non-methane organic compounds (NMOCs). Periodic monitoring of specific NMOCs may also be required to verify they are not migrating off-site.

5.3.2. *In-probe Acceptable Levels.* In-probe methane levels should be monitored with an infrared landfill gas analyzer. A methane concentration greater than 5 percent in a monitoring probe indicates the potential for explosive conditions. Adjustments to the gas collection system's operating procedures should be made if methane levels exceed some specified level (typically 0.5 to 5 percent) 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 gas concentrations exceed acceptable levels, probes will be monitored at an increased frequency (as frequently as once per day). If well readings indicate gas is escaping off-site, consideration should be given to monitoring off-site structures to ensure landfill gas 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 location where gas could potentially collect.

5.3.4. *Enclosed Structure Monitoring.* Gas 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 hand held gas meter at the following locations:

- The base of each exterior wall.
- Underground utility lines leading into the building.
- Ambient air in each room of the building.

A continuous monitoring device, with alarm, should be installed in structures that are frequently occupied. Methane concentrations should not exceed 25 percent of the lower explosive limit (1.25 percent methane).

5.3.5. *Surface Emission Monitoring.* Surface emission monitoring is typically performed at large municipal 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 gas. A summary of surface emission testing procedures can be found in the reference entitled "Landfill Gas Operation and Maintenance Manual of Practice."

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 and situations where oxygen has been displaced by landfill gas require use of an infrared landfill gas analyzer. A photoionization detector or portable field gas chromatograph should be used to monitor for low level toxic air contaminants that may exist in landfill gas. Several specific instruments are common to LFG control systems that should be considered during design. These include:

- Combustible gas indicators (CGI).
- Photoionization detector/Infrared landfill gas analyzers.
- Process gas chromatographs (GC).

Process GCs can be used for onsite 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 gas measurements in migration probes. The catalytic oxidation type of CGI measures the concentration of a combustible gas in air, indicating the results in parts per million or in percent of the LEL. Often these readings are taken in conjunction with oxygen readings. These instruments operate by the detection method of a platinum filament being heated by the combustion of the gas 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 parts per million by volume (ppmv) and the other in percent of the LEL. Limitations to this equipment are as follows:

- The reaction is temperature dependent and is, therefore, only as accurate as the incremental difference between calibration and ambient sampling temperatures.
- Sensitivity is a function of the physical and chemical properties of the calibration gas therefore methane should be used as the calibration standard.
- The unit will not work in oxygen deficient or oxygen enriched atmospheres.
- Certain compounds such as leaded gas, 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 yearly 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.* High concentrations of methane (greater than 100% of the LEL or 5% methane) are measured with a combustible gas indicator 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 and at higher concentrations, the TC sensor is used to measure up to 100% gas 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 gas is not involved.

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 landfill gas. However, since landfill gas is comprised of a combination of different gases, readings on the meter will vary depending on the concentration of the other gases 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. 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 and 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.

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 in landfill gasses because oxygen levels can be very low.

5.4.2. *Flame Ionization Detector (FID)/Organic Vapor Analyzer (OVA).* FIDs measure many organic gases and vapors. Some FIDs are commonly referred to as Organic Vapor Analyzers or 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 gas chromatograph (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.

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.

5.4.3. *Infra-Red (IR) Analyzer.* 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 (gas). 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 gas known to be present. The advantage of IR analyzers is that the high carbon dioxide levels found in landfills will not affect methane readings.

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 calibrant gases should be used if monitoring levels in gas extraction wells.

5.5. **Condensate Collection and Treatment.** Disposal of gas 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.* Landfill gas 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.* Subtitle D 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 (i.e., incineration). This technology can typically destroy up to 1 gpm of condensate. The popularity of this method of disposal is increasing. Aspiration of

condensate into LFG flares has been accomplished on several sites and promises to be an efficient and effective method of condensate disposal, provided the condensate is non-hazardous. Flare destruction efficiency is dependent on: 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 gas 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 Btu's 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.

5.5.4. *Summary.* Data that have been published shows that the aqueous phase of LFG condensate generally passes the TCLP regulated limits. If a non-aqueous phase liquid is present in the condensate, this fraction has been found to fail ignitability testing. Landfills that have been operating principally as municipal landfills are rarely found to have a significant non-aqueous phase fraction.

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 gas flow rate at the station may need to be adjusted due to changes in the landfill gas 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/fare system.

5.6.1. *Blower*

5.6.1.1. *Monitoring Requirements.* Inspection of this unit should include reading the flow rate and pressure of the system and comparing these measurements to a standard curve developed by the manufacturer to determine whether the blower is operating within a safe range for the equipment. The pressure drop across the blower should also be monitored using magnehelic gages at entrance and exit ports on the blower. The blower should also be inspected and monitored according to manufacturer's specifications for the unit.

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 gas 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:

- Gas-flow rates.
- Gas supply pressure.
- Minimum operating temperatures.
- Influent gas parameters including CH_4, CO_2, and O_2.

5.6.3.1.1. Manufacturer'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 CH_4 content and flow rate of the influent gas 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 (1800 F)) are observed, controls for these louvers should be inspected.

5.6.3.1.3. Gas parameters including CH_4, O_2 and CO_2 should be inspected to insure 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. Additional operating parameters including gas flow rates; gas supply pressure; minimum operating temperature; and inflow LFG parameters should be monitored more regularly.

5.7. **Maintenance Requirements.** The operation and maintenance (O&M) of a LFG management system should be structured to maintain the operation goals (i.e., 98 percent reduction of NMOC). An O&M program can be divided into the following categories:

- Routine O&M.
- Non-routine maintenance.
- 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:

- Extraction wells.
- Collection header.
- Monitoring wells and probes.
- Oil change on blower.
- Flame arrestor cleaning.
- Condensate handling.
- Gas detection system.
- Pilot/auxiliary fuel.

Pilot/auxiliary fuel refilling and equipment cleaning should be performed at least weekly. In particular, the combustion mechanism will require 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.

Regular oil and lubrication changes should also be performed on the blower, 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 larger 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:

- Repair or replacement of failing components.
- 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:

- Responding to system failure or shut down.
- 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 so as to collect as much gas as practicable and or contain the LFG in all parts of the landfill. For example, the gas flow rate at the station may need to be adjusted due to landfill aging. Partially opening or closing the valve on the blower inlet side or adjustments at individual extraction wells usually accomplishes adjustments of flow 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 must then be made until the situation is corrected.

CHAPTER 6
Regulatory Requirements

6.1. **Introduction**. This chapter discusses environmental regulations as they pertain to landfill gas 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 landfill 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 regulatory framework under which the LFG control is being done (e.g., CERCLA remediation, RCRA Corrective Action, etc.) in order to determine which, if any of the following requirements must be met.

6.1.1. 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 landfill gas 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 including:

- The RCRA which regulates solid and hazardous waste management such as the landfill itself.
- The CAA which regulates air emissions.
- The 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. **RCRA Regulations**. Under RCRA, if LFG is emitted or condensate is treated and/or disposed of, 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]
- 40 CFR Part 262 [regulations pertaining to generator requirements]
- 40 CFR Part 268 [regulations for 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, substantive requirements such as physical storage requirements and containers will most likely have to be complied with.

6.4. **CAA 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. 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:

- New Source Performance Standards (NSPS) found at 40 CFR Part 60
- National Emission Standards for Hazardous Air Pollutants found at 40 CFR 63
- Title V Operating Permits found at 40 CFR Part 70
- State and local air quality regulations

6.4.1. EPA 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.

6.5. **CWA Regulations.** Under the CWA, if LFG condensate is disposed of by treatment and effluent discharge to Waters of the United States, discharge permits may be required and effluent concentrations/limits may be required to meet a state's water quality standards. Effluent analyses required for all discharge permits can include:

- Biochemical Oxygen Demand (BOD).
- Chemical Oxygen Demand (COD).
- Total Organic Carbon (TOC).
- Total Suspended Solids (TSS).
- Ammonia (as N).
- Temperature.
- pH.
- Flow.

6.5.1. Response actions taken under CERCLA (IRP, FUDS, BRAC or Superfund) are not required to obtain 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 Waters of the U.S.

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 will be imposed by the local POTW 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. Refer to each Federal statute to determine the scope of this application of Federal, State and local law to Federal facilities. 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 in order to ensure compliance with applicable regulations.

APPENDIX A
References

A.1. Required Publications

A.1.1. *Government Publications*

A.1.1.1 *Army*

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Soil Vapor Extraction and Bioventing. http://www.usace.army.mil/publications/

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A.1.1.2 *U.S. Environmental Protection Agency*

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**APPENDIX B
Landfill Off-Gas Collection System Calculations**

B.1. **General**. The following is a hypothetical example that illustrates the calculations used in the design of an off-gas collection and treatment system (Emcon Associates 1980).

B.1.1. *Site Background Information.* The 25-acre Westslope Landfill is located near Omaha, Nebraska and accepted municipal, industrial and construction debris from the neighboring communities from 1970 to 1995. In 1972 the state required a 6-inch daily cover be used to minimize odors. In 1999, the State required that the landfill be closed with a multi-layer cap composed of a 6 inch grading layer, a 40-mil HDPE geomembrane, a geonet drainage layer, and 24 inches of cover soil. The State also required that an active gas control system be installed to limit off-site subsurface migration of landfill gas to 10% of the LEL for methane. A housing development is located adjacent to the landfill on the south side of Center Street. A plan view of the site is shown in Figure B.1.

B.1.2. *Site Geology.* Bedrock consisting of weathered limestone underlies the site at approximately elevation 980 in the central area of the landfill. The bedrock slopes gently to the east. The overburden soils consist of 20 to 30 feet of silty sand. Ground water fluctuates seasonally at the site and is approximately 15 feet below the original ground surface.

B.1.3. *Objective*

- Design an active landfill gas collection system that consists of vertical extraction wells to prevent the off-site migration of gas.
- Design an enclosed flare to destroy methane and non-methanogenic organic compounds (NMOCs) in the collected gas.

B.2. **Site Characteristics**

- Landfill footprint = 25 acres
- Volume of waste = 1,700,000 cy

B.3. **Refuse Characteristics**

- Average age of Refuse = 20 to 25 years
- In-Place Refuse Density = 1,200 lbs/cy
- Capping Material = 40 mil HDPE
- Maximum Depth = 45 feet
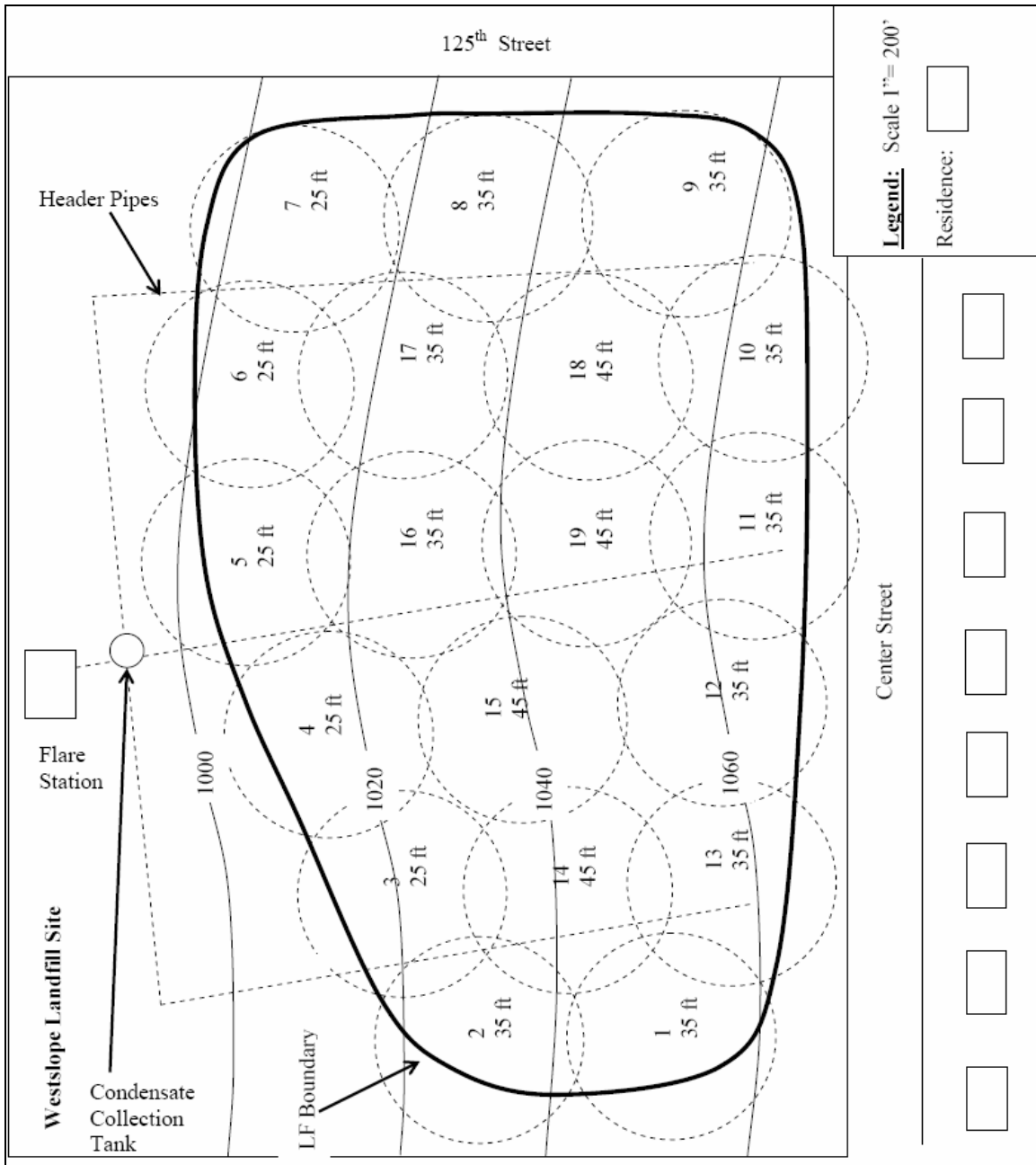
Figure B.1. Plan View of the Site.

B.4. **Gas Characteristics**

- Landfill gas emission rate $= 1.6 \times 10^{-4}$ ft^3/(lb day)
- Concentration of methane in gas $= 50$ percent
- Assumed radius of influence of extraction wells $= 150$ feet
- Temperature of landfill gas $= 110$°F
- Landfill Gas Viscosity $= 2.58 \times 10^{-7}$ lb s/ft^2

B.5. **Calculations for the Off-Gas Collection System**

B.5.1. *Sample Problem Design Calculations*

B.5.1.1. *General Assumptions.*

V = volume of waste (1,700,000 cy)
D = density of waste (45 lb/ft^3)
G = methane production rate $= 1.6 \times 10^{-4}$ ft^3/(lb day)

B.5.1.2. *Flow Rate for Entire Landfill.*

$Q_{tot} =$ (volume of waste)(D)(G)
$Q_{tot} =$ (1,700,000 yd^3)(27ft^3/yd^3)(45lb/ft^3) [1.6×10^{-4} ft^3/(lb day)]
$Q_{tot} =$ 330,480 ft^3/day $= 230$ ft^3/min (methane)

As methane is 50% of the landfill gas produced, the total flow rate of extracted landfill gas is:

2×230 ft^3/min $= 460$ ft^3/min

B.5.1.3. *Determine Flow Rates from a particular well (Cylinder Method).*

$Q = \pi (R^2 - r^2) t D G$

where:

Q = methane flow rate
R = radius of influence
r = borehole radius (assumed to be 12 inches for all wells [which is negligible])
t = waste thickness
D = density of waste (45 lb/ft^3)
G = methane production rate [1.6×10^{-4} ft^3/(lb day)]

B.5.1.3.1. *For 25-Foot-Deep Wells.*

R = 150 feet, t = 25 feet

$Q = \pi (150)^2 (25 \text{ ft})(45 \text{ lb/ft}^3)[1.6 \times 10^{-4} \text{ ft}^3/(\text{lb day})] = 12{,}723 \text{ ft}^3/\text{day}$

Q = 8.84 ft^3/min (methane only)

Since landfill gas is 50% methane:

Landfill gas flow = 2 × 8.84 = 17.7 ft³/min.

B.5.1.3.2. *For 35-Foot-Deep Wells.*

R = 150 feet, t = 35 feet

$Q = \pi (150)^2 (35 \text{ ft})(45 \text{ lb/ft}^3)[1.6 \times 10^{-4} \text{ ft}^3/(\text{lb day})] = 17{,}812 \text{ ft}^3/\text{day}$

Q = 12.4 ft^3/min (methane only)

Landfill gas flow = 2 × 12.4 = 24.8 ft³/min.

B.5.1.3.3. *For 45-Foot-Deep Wells.*

R = 150 feet, t = 45 feet

$Q = \pi (150)^2 (45 \text{ ft})(45 \text{ lb/ft}^3)[1.6 \times 10^{-4} \text{ ft}^3/(\text{lb day})] = 22{,}900 \text{ ft}^3/\text{day}$

Q = 15.9 ft^3/min (methane only)

Landfill gas flow = 2 x 15.9 = 31.8 ft³/min

5 wells at 17.6 ft^3/min   = 88 ft^3/min
10 wells at 24.8 ft^3/min = 248 ft^3/min
4 wells at 31.8 ft^3/min   = 127 ft^3/min
Total   = 463 ft^3/min

B.5.1.4. *Determine Pressure Drop Required at Each Well to Maintain Assumed Radius of Influence.*

$$\Delta P = \mu G_{\text{tot}} D \left[R^2 \ln(R/r) + (r^2/2) - (R^2/2) \right] / 2 K_s$$

where:

ΔP = pressure difference from the outer edge of the radius of influence to the gas vent
R = radius of influence
r = radius of borehole (assumed to be 12 inches for all wells)
μ = absolute viscosity of the landfill gas (1.21×10^{-5} N s/m^2 = 2.581×10^{-7} lb s/ft^2)
K_s = apparent permeability of the refuse (assumed to be 15 Darcy = 2.29×10^{-8} in.^{2})
D = density of the refuse (45 lb/ft^3)
G_{tot} = total landfill gas production rate (assumed to be $2 \times 1.6 \times 10^{-4}$ ft^3/(lb day).

B.5.1.4.1. *For All Wells, M (Melema Factor)* = $\mu G_{tot} D / 2 K_s$

M = [(2.581×10^{-7} lb s/ft^2)(2)[1.6×10^{-4} ft^3/(lb day)](45 lb/ft^3) (day/86,400 s)] / [(2)(2.29 $\times 10^{-8}$ in.^{2})(1 ft^2/144 in.^{2})]

M = 1.314×10^{-4} lb/ft^4

B.5.1.4.2. *For All Wells, Assumed Radius of Influence is 150 Feet.*

ΔP = $M [R^2 \ln(R/r) + (r^2/2) - (R^2/2)]$
    = 1.314×10^{-4} lb/ft^4 [(150ft)^2 ln(150 ft/1 ft) + {(1 ft)^2/2) - (150 ft)^2/2}]
    = 1.314×10^{-4} lb/ft^4 [101,489 ft^2]
    = 13.33 lb/ft^2
    = 2.57 inches of water column.

B.5.2. *Header Pipe Sizing.* Pipe sizing is a trade off between the capital cost of the pipe and the energy requirements of the blower. The higher cost of larger pipe must be balanced against lower horsepower requirements of the blower due to less pressure loss due to friction.

- Header pipe size = 6 inches
- Connector pipes from wells to headers = 2 inches

B.5.3. *System Curve.* The system curve is determined by computing all head losses through the system at various flow rates due to the following:

- Subsurface head loss.
- Head loss in pipes.
- Head loss through fittings and valves.

The friction losses from the subsurface, the straight pipe lengths, and the valves and fittings are added together to obtain the total friction loss at a given flow rate. Note that these calculations are performed assuming that the valves are fully open.

B.5.3.1. *Subsurface Head Loss.* Assume 2.57 inches as computed in paragraph B-5.1.

B.5.3.2. *Calculate Pipe Head-Loss.* The most common method of predicting friction losses in straight pipes is to use the Darcy-Weisbach equation:

$$h_f = f\,(L/d)(v^2/2g)$$

where:

h_f = head loss, m (ft) of fluid
f = friction factor for the pipe, dimensionless (dimensionless)
L = length of segment, m (ft)
d = inside pipe diameter, m (ft)
v = average velocity of the flow, m/sec (ft/s)
g = acceleration due to gravity (9.81 m/s² = 32.2 ft/s²).

The head loss calculated by this formula is in feet of landfill gas. The ideal gas law can be used to estimate the density of the gas passing through the header pipe. Estimate the gas density to convert pressure in feet of landfill gas to inches of water column (in wc).

Gas Density = $PM/R_U T$

where:

P = absolute pressure within header pipe
Assuming 30 in. wc vacuum
1 atm = 407.2 inches of water column (in wc)
P = (407.2 in. wc −30 in. wc) /407.2 in. wc = 0.926 atm
M = molecular weight of landfill gas
= 0.5 (molecular weight methane, CH_4) + 0.5(molecular weight of carbon dioxide, CO_2)
= 0.5 (12+4) + 0.5 (12+2x16) = 30 kg/kg-mole
R_U = Universal gas constant
= 0.0821 L-atm/g-mole K
T = Absolute Temperature
= 110ºF = 43.3ºC + 273.16ºK = 316.5ºK.

Landfill Gas Density = $PM/R_U T$
= [(0.93 atm) × (30 kg/kg-mole)] / [(0.0821 L-atm/ g-mole K) × (316.3 K) × (1000 g-mole/kg-mole)]
= $1.069 × 10^{-3}$ kg/L

Landfill Gas Density = (0.001069 kg/L × 2.205 lb/kg × 28.32 L/ft³
            = 0.0668 lb/ft³

1 pound-force/square inch (PSI) = 27.6799048 inch of water [4 °C]

To convert feet of landfill gas to inches of water column, the following factor (F') must be applied:

F' = 0.0668 lb/ft³ × 1 ft²/144 ft²/in.² × 27.7 in. wc/(lb/in.²)
         = 0.01284 in. wc/ft

Head Loss, in. wc = 0.01284 × $fLV^2/2d$ × g = 0.0002 fLV^2/d.

B.5.3.3. *Head Loss Through Valves and Fittings.* There are two primary methods for estimating head losses through valves and fittings.

- Look up k values in tables (where $k = f L/d$ and, therefore, $h_f = k\, v^2/2g$).
- Use tabulated values of equivalent length of straight pipe. For example, the resistance in a 6-inch standard tee is equivalent to that of approximately 30 feet of 6-inch straight pipe.

B.5.3.4. *Landfill Gas Piping Flow Diagram.* The piping system consists of headers that connect to 19 wells in three manifolds (Figure B.2). The manifolds connect to a flare stack through a condensate knockout tank, blower, and flame arrestor.
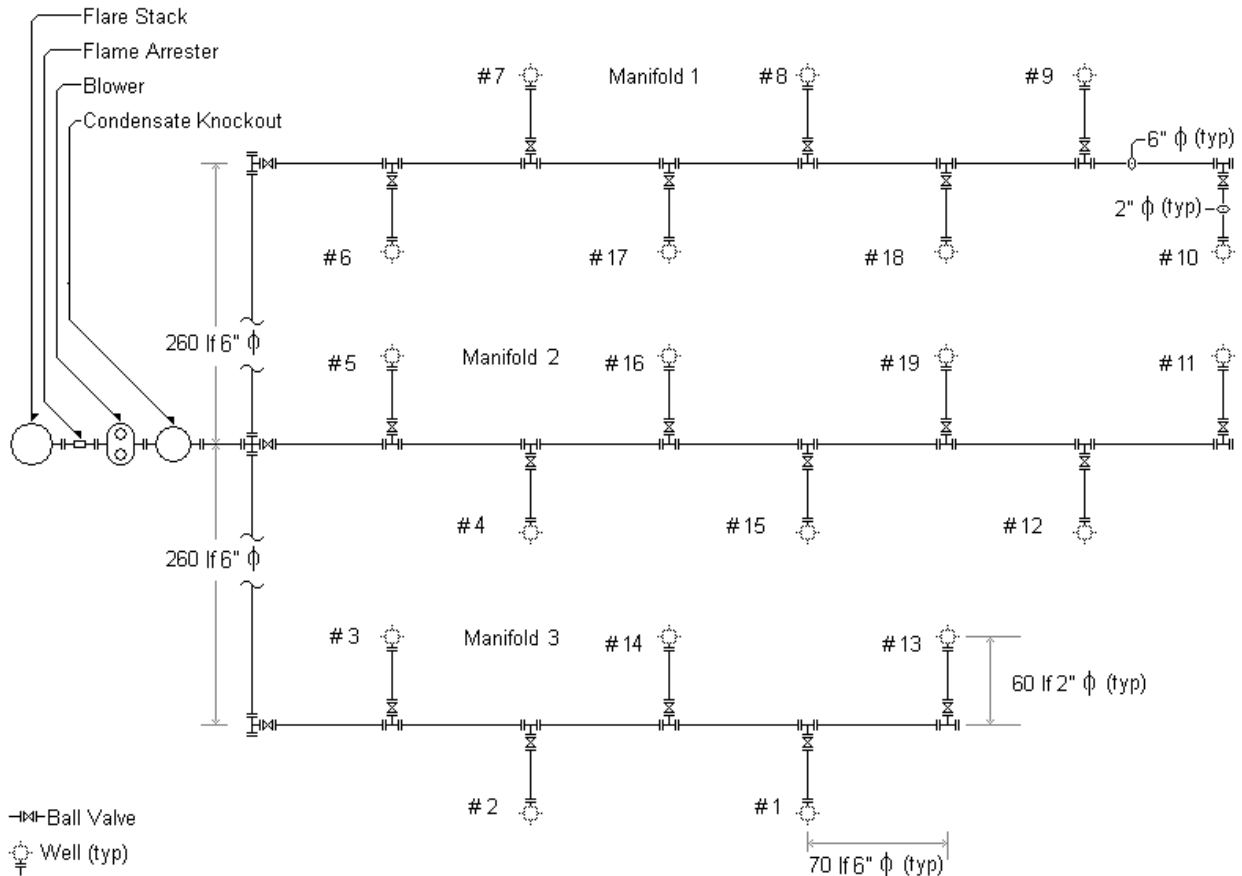
Figure B.2. Landfill Gas Piping Flow Diagram.

B.5.3.5. *Manifold 1 Calculations.* Different flow rates were used for wells installed with different screen lengths: 17.6 scfm for the 25-foot wells, 24.8 scfm for the 35-foot wells, and 31.8 scfm for the 45-foot wells. The wells are connected to a common header. The pressure loss from each well to a common point in the header was calculated to establish the required header vacuum. Following is the example calculation for header # 1. Calculations for headers #2 and #3 are similar.

B.5.3.5.1. *Well Number 10.* The approximate head loss from well #10 (flow rate of 24.8 scfm) including soil head loss (2.57 in. wc) plus wellhead losses (2.00 in. wc) plus discharge piping losses to header 1 at point b (0.668 in. wc) is 5.238 in. wc vacuum.
The following piping head losses are additive to point j:

- 0.005 in. wc vacuum—approximate b–c piping head loss
- 0.017 in. wc vacuum—approximate c–d piping head loss

- 0.039 in. wc vacuum—approximate d–e piping head loss
- 0.062 in. wc vacuum—approximate e–f piping head loss
- 0.090 in. wc vacuum—approximate f–g piping head loss
- 0.099 in. wc vacuum—approximate g–h piping head loss
- 0.132 in. wc vacuum—approximate h–i piping head loss
- 0.454 in. wc vacuum—approximate i–j piping head loss
- The total head loss from well 10 to point j is 6.136 in. wc.

B.5.3.5.2. *Well Number 18.* The approximate head loss from well #18 (flow rate of 31.8 scfm) including soil head loss (2.57 in. wc) plus wellhead losses (3.288 in. wc) plus discharge piping losses to header 1 at point d (1.099 in. wc) is 6.957 in wc vacuum.

The following piping head losses are additive to point j:

- 0.039 in. wc vacuum—approximate d–e piping head loss
- 0.062 in. wc vacuum—approximate e–f piping head loss
- 0.090 in. wc vacuum—approximate f–g piping head loss
- 0.099 in. wc vacuum—approximate g–h piping head loss
- 0.132 in. wc vacuum—approximate h–i piping head loss
- 0.454 in. wc vacuum—approximate i–j piping head loss
- The total head loss from well 18 to point j is 7.833 in. wc.

B.5.3.5.3. *Well Number 7.* The approximate head loss from well #7 (flow rate of 17.6 scfm) including soil head loss (2.57 in. wc) plus wellhead losses (1.007 in. wc) plus discharge piping losses to header 1 at point g (0.337 in. wc) is 3.914 in. wc vacuum. The following piping head losses are additive to point j:

- 0.0099 in. wc vacuum—approximate g–h piping head loss
- 0.0132 in. wc vacuum—approximate h–i piping head loss
- 0.454 in. wc vacuum—approximate i–j piping head loss
- The total head loss from well 7 to point j is 4.39 in. wc.

B.5.3.6. *Head Losses to the Blower Intake.* The total head loss from well #18 to point j exceeds the losses from well #10 and also well #7 to point j (Table B-1 and Figure B.3). Therefore the head loss in well #18 and associated piping determines the required the header vacuum. Control valves at the other wells will have to be throttled to maintain the required flow rates at those wells. The blower vacuum required is equal to the head losses to point j (7.833 in. wc) + point k–l (0.888 in. wc) + the condensate tank (2.00 in. wc) + point m–n (0.335 in. wc) = 11.076 in. wc.

B.5.3.7. *Calculations for Combined Flow to the Flare Stack.* Refer to the flow sheet (Figure B.4 and Table B-2) for piping from point j through the condensate knock out tank, blower, flame

arrestor, and stack. The 12.444 in. wc blower discharge head requirement is the sum of head losses from point o to the stack discharge at ambient atmospheric pressure. The 12.444 in. wc represents the pressure exerted on the discharge side of the blower resulting from the various pieces of equipment attached to the discharge side of the blower.

Manifold 1				
Well or Pipe	Flow (scfm)	ΔP (in H_2O)		
		Soil	Well Head	Piping
# 10	24.8	-2.57	-2.000	- 0.668
b - c	24.8			- 0.005
# 9	24.8	-2.57	-2.000	- 0.668
c - d	49.6			- 0.017
# 18	31.8	-2.57	-3.288	- 1.099
d - e	81.4			- 0.039
# 8	24.8	-2.57	-2.000	- 0.668
e - f	106.2			- 0.062
# 17	24.8	-2.57	-2.000	- 0.668
f - g	131.0			- 0.090
# 7	17.6	-2.57	-1.007	- 0.337
g - h	148.6			- 0.099
# 6	17.6	-2.57	-1.007	- 0.337
h - i	166.2			- 0.132
i - j	166.2			- 0.454

Maximum Total Headloss from any point to j is the headloss from Well #18 to j = - 7.833 in H_2O.
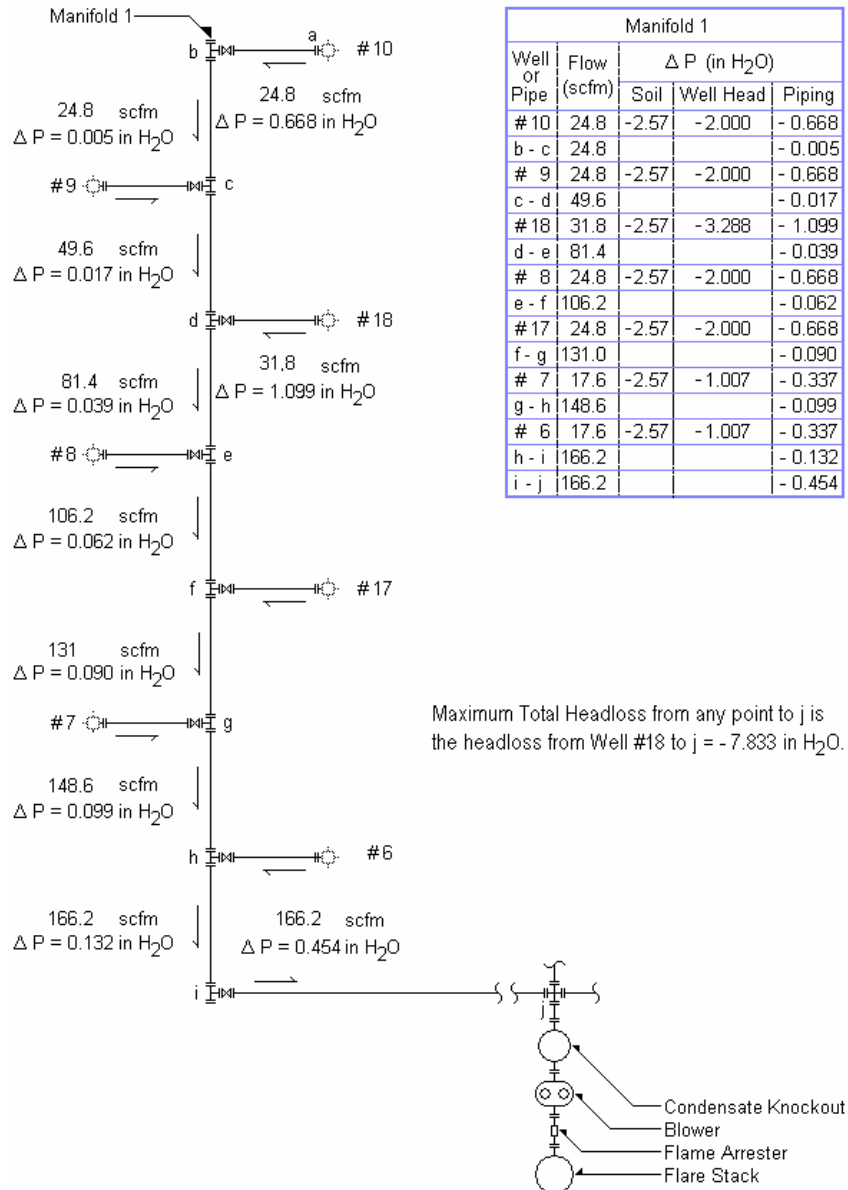
Figure B.3. Piping Head Loss Diagram

Table B-1. Piping Head Loss Calculations

Landfill Gas Piping System - Manifold 1

Dimensions of Schedule 40 HDPE Pipe

Nom I. D.   Cross-Sectional Area.

LFG Composition: 50% Methane, 50% Carbon Dioxide

MW LFG : 0.5(16) + 0.5(44) = 30

in.	in.	in.^{2}	ft^2		
2	2.067	3.356	0.02331	Density LFG	0.067183 lb/ft^3
3	3.068	7.393	0.05134	Temperature LFG	110ºF
4	4.026	12.730	0.08840	Absolute Viscosity LFG	2.58×10^{-7} lb(force) s/ft2
6	6.065	28.890	0.20063	Absolute Viscosity LFG	8×10^{-6} lb(mass)/ft s
8	7.981	50.030	0.34743	$Re = Dvp/u$	
10	10.020	78.850	0.54757	Head Loss, in. wc $= (0.0.0002007)fL(v^2)/D$	

Node From	Thru	Component Type	Flow Rate CFM	Nom I.D. In.	I.D.,ft	X-Sect Vel FPS	Pipe L, ft	Ftg Loss Coef	Ftg Equiv ft pipe	Reynolds Number Re	Friction Factor f	Well h.l. in wc	Pipe h.l. in. wc	Ftg h.l. in. wc	Total h.l. in. wc
a	b	well 10	24.8									2.57			2.570
		well head	24.8	2								2			2.000
		piping	24.8	2	0.1723	17.74	60			2.47×10^4	0.0270		0.5937		0.594
		ball valve	24.8	2											0.000
		2x6	24.8	2				43	7.4					0.0732	0.073
		Tee(branch)	24.8	6	0.5054	2.06	60	30		8.42×10^3	0.0302			0.0015	0.002
		Sub-Total													5.238
18	d	well 18	31.8									2.57			2.570
		well head	31.8	2								3.288			3.288
		piping	31.8	2	0.1723	22.74	60			3.17×10^4	0.0270		0.9762		0.976
		ball valve	31.8	2				0	0.0					0.00000	0.000
		2X6	31.8	2				43	7.4					0.12051	0.121
		Tee(branch)	31.8	6	0.5054	2.64	60	30.0		1.08×10^4	0.0300			0.00249	0.002
		Sub-Total													6.958
7	g	well 7	17.6									2.57			2.570
		well head	17.6	2								1.007			1.007
		piping	17.6	2	0.1723	12.59	60			1.75×10^4	0.0270		0.2990		0.299
		ball valve	17.6												0.000
		2x6	17.6	2				43	7.4					0.03688	0.037
		Tee(branch)	17.6	6	0.5054	1.46	60	30.0		5.98×10^3	0.0350			0.00089	0.001
		Sub-Total													3.914
b	c	piping	24.8	6	0.5054	2.06	70			8.42×10^3	0.0302		0.0036		0.004
		Tee(run)	24.8	6	0.5054	2.06	20	10.0						0.00051	0.001
		Sub-Total													0.004

Node From	Thru	Component Type	Flow Rate CFM	Nom I.D. in	I.D.,ft	X-Sect Vel FPS	Pipe *L*, ft	Ftg Loss Coef	Ftg Equiv ft pipe	Reynolds Number *Re*	Friction Factor *f*	Well h.l. In. wc	Pipe h.l. In. wc	Ftg h.l. In. wc	Total h.l. In. wc
c	d	piping	49.6	6	0.505 4	4.12	70			1.68×10^4	0.0276		0.0130		0.013
		Tee(Run)	49.6	6				20	10.0					0.00372	0.004
		Sub-Total													0.017
d	e	piping	81.4	6	0.505 4	6.76	70			2.76×10^4	0.0270		0.0343		0.034
		Tee(Run)	81.4					20	10.0					0.00490	0.005
		Sub-Total													0.039
e	f	piping	106.2	6	0.505 4	8.82	70			3.61×10^4	0.0251		0.0543		0.054
		Tee(Run)	106.2					20	10.0					0.00776	0.008
		Sub-Total													0.062
f	g	piping	131	6	0.505 4	10.88	70			4.45×10^4	0.0240		0.0791		0.079
		Tee(Run)	131					20	10.0					0.01129	0.011
		Sub-Total													0.090
g	h	piping	148.6	6	0.505 4	12.35	70			5.05×10^4	0.0230		0.0975		0.097
		Tee(Run)	148.6					20	10.0					0.00139	0.001
		Sub-Total													0.099
h	I	piping	166.2	6	0.505 4	13.81	70			5.64×10^4	0.0218		0.1155		0.116
		Tee(Run)	166.2					20	10.0					0.01650	0.017
		Sub-Total													0.132
i	j	ell	166.2	6	0.505 4	13.81		30	15.0	5.64×10^4	0.0218			0.02476	0.025
		piping	166.2	6	0.505 4	13.81	260			5.64×10^4	0.0218		0.4292		0.429
		Sub-Total													0.454

	Unit	Flow (scfm)	ΔP (in H₂O)
j	Manifold Vacuum	463.2	– 7.833
k - l	Pipe and Fittings	463.2	– 0.888
l - m	Condensate Knockout	463.2	– 2.00
m - n	Pipe and Fittings	463.2	– 0.355
n	Blower Inlet Vacuum	463.2	– 11.076
o - p	Pipe and Fittings	463.2	+ 0.355
p - q	Flame Arrestor	463.2	+ 2.000
q - r	Pipe and Fittings	463.2	+ 0.089
s	Stack	463.2	+ 10.000
o	Blower Discharge Pressure	463.2	+ 12.444

173.2 scfm
From
Manifold 2

166.2 scfm
From
Manifold 1

123.8 scfm
From
Manifold 3

j

k

20'

463.2 scfm

l

Condensate Knockout

m

20'

n

Blower

o

20'

p

Flame Arrestor

q

5'

r

s Flare Stack

Figure B.4. Discharge Pressure Diagram

Table B-2.
Blower Discharge Pressure Calculations

Landfill Gas Piping System - Combined flow to stack

Dimensions of Schedule 40 HDPE Pipe				LFG Composition: 50% Methane, 50% Carbon Dioxide	

Nominal I. D.   Cross-Sectional Area.   MW LFG : 0.5(16) + 0.5(44) = 30

in.	in.	in.^{2}	ft^2	Density LFG	0.067183 lb/ft^3	
2	2.067	3.356	0.02331	Temperature LFG	110 deg F	
3	3.068	7.393	0.05134	Absolute Viscosity LFG	2.58×10^{-7}	lb(force) s/ft2
4	4.026	12.730	0.08840	Absolute Viscosity LFG	8.31×10^{-6}	lb(mass)/ft s
6	6.065	28.890	0.20063			
8	7.981	50.030	0.34743	$Re = Dvp/u$		
10	10.020	78.850	0.54757	Head Loss, in. wc $= (0.0.0002007)fL(v^2)/D$		

Node		Component	Flow	Nom	I.D.	X-Sect	Pipe	Ftg	Ftg	Reynolds	Friction	Well	Pipe	Ftg	Press
		Type	Rate	Dia	ft	Vel	L, ft	Loss	Equiv	Number	Factor	h.l.	h.l.	h.l.	
From	Thru		CFM	In.		FPS		Coef	ft pipe	Re	f	in. wc	in. wc	in. wc	in. wc
j	j														−7.833
k	l	piping	463.2	6	0.5054	38.48	20			1.57×10^5	0.0302		0.3552		−0.355
		Tee(Branch)	463.2		0.5054	38.48		60	30.0						0.53271	−0.533
		Sub-Total														−0.888
l	m	condensate tank														−2.000
m	n	piping	463.2	6	0.5054	38.48	20			1.57×10^5	0.0302		0.3554		−0.355
n	n	blower inlet vacuum														−11.076
o	p	piping	463.2	6	0.5054	38.48	20			1.57×10^5	0.0302		0.3554		0.355
p	q	flame arrestor														2.000
q	r	piping	463.2	6	0.5054	38.48	5			1.57×10^5	0.0302		0.0888		0.089
r	s	stack														10.000
n	o	blower discharge pressure														12.444

B.5.4. *Blower Selection Considerations.* Three criteria are used to size the blower: flow (463 SCFM), head loss on the suction side of the blower (11.076 in. wc), and discharge head on the outlet side of the blower (12.444 in. wc). Based on these criteria, manufacturer's catalogs are used to select a blower that can meet these criteria. It is important to select a blower that only minimally exceeds the calculated requirements to avoid exceeding the capacity of any of the in-line treatment processes.

It is a difficult task to select a blower that will remain in an efficient operating range over the long-term because gas production varies during the life of the landfill. Consideration should be given to selection of a variable frequency blower motor drive for energy conservation and greater operating flexibility as the generation of landfill gas decreases over time.

B.5.5. *Condensate Production Rate.* Assume air is extracted at 100% relative humidity and remains at 100% relative humidity as it travels from the extraction well to the blower. Determine the amount of condensate removed as a result of the temperature drop of the gas. The gas is assumed to be at its maximum temperature as it exits the well. The gas will drop in temperature as it travels through the header piping. The length of travel, location of the header pipe, and the ambient temperature will determine the magnitude of the temperature drop over the section of header piping for which condensate generation is being computed.

A rough estimate of the amount of condensate generated can be determined using psychrometric charts for air. The following assumptions were made in order to compute the amount of condensate produced.

B.5.5.1. *Flow Rate.* The flow rate was determined to be 463 ft^3/min (218 L/s) in the above calculations.

B.5.5.2. *Temperature.* The temperature of the gas exiting the landfill is 110°F (316.3 K) and drops 20° to 90°F (305 K) as it travels to the blower system.

B.5.5.3. *Potential Condensate Generated.* Psychrometric charts can be used to estimate saturated water vapor concentration at different temperatures:

Conc. of water vapor = 0.059 kg water/kg landfill gas (at 316.3 K)

Conc. of water vapor = 0.031 kg water/kg landfill gas (at 305 K)

Subtracting:

Potential Condensate = 0.028 kg water/kg landfill gas

Note that most psychometric charts are created for higher pressures than are typically found in the header pipes of a LFG collection system. However, using these charts will generally not introduce large error when estimating condensate generation.

Density of landfill gas = 1.074 $\times10^{-3}$ kg/l = .067 lbs/ft^3

The flow rate times the concentration of the condensate yields the following condensate generation rate:

(0.028 kg water/kg LF gas) × (1.074 × 10^{-3} kg/L) × (218 L/s) × (86,400 s/day) × (1 L/kg) = 566 L/day = 150 gal/day.