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Technical Letter
No. 1110-1-160 17 April 1995

Engineering and Design
LANDFILL OFF-GAS COLLECTION AND TREATMENT SYSTEMS

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1. Purpose. This engineering technical letter (ETL) was written to provide guidance for designers to determine appropriate application of Landfill Off-Gas Collection and Treatment Systems, and to properly design and specify these systems.

2. Applicability. This ETL applies to all HQUSACE elements, major subordinate commands (MSC) , districts, laboratories, and field operating activities having military or civil works design responsibilities. The engineering and design procedures are applicable to all Corps of Engineers projects. Collection and Treatment of landfill off-gas is a requirement at both Federal and municipal sites, including Department of Defense installations. This ETL was written primarily for sites containing Municipal Waste, Hazardous and Toxic Wastes and does not apply to Radioactive Waste sites.

3. References. This ETL should be used in conjunction with design guidance documents listed in this paragraph as well as those listed in Appendix D.

a. EM 385-1-1, safety and Health Requirements Manual.

b. ER 385-1-92, Safety and Occupational Health Document Requirements for Hazardous, Toxic and Radioactive Waste (HTRW) Activities.

c. ER 1110-1-263, Chemical Data Quality Management for Hazardous Waste Remedial Activities.

d. ER 1110-345-100, Design Policy for Military Construction.

e. ER 1110-345-700, Design Analyses.

g. ER 1110-345-710, Design Drawings.

h. ER 1110-345-720, Construction Specifications.

i. TM 5-814-5, Sanitary Landfill.

4. Discussions. The attached appendices present the procedures and considerations associated with the engineering and design of landfill off-gas collection and treatment systems. The following appendices are attached:

a. Appendix A - Design Considerations: The information presented in this appendix provides a comprehensive overview of design and engineering considerations for Landfill Off-Gas Collection and Treatment, including:

(1) Background information, theory, and definitions.

(2) Theories of operations for passive and active gas collection systems and gas treatment for energy recovery systems.

(3) A summary of off-gas collection and treatment applicability, a comparison of options, and typical operating performance.

(4) An overview of design considerations from gas collection through gas treatment and recovery or disposal and specific design considerations for components of the Landfill Off-Gas Collection and Treatment equipment and associated accessories and auxiliary systems.

(5) A summary of legal requirements and permits.

(6) Emissions characterization and treatability studies.

(7) Equipment sizing criteria.

(8) Construction materials and installation specifications.

(9) Operation and Maintenance.

(10) Design and construction package requirements.

b. Appendix B - Design Calculations. This appendix presents the types of calculations and documents associated with Landfill Off-gas Collection and Treatment applications.

c. Appendix C - Definitions and Acronyms. This appendix presents the definitions and acronyms of terms used throughout the ETL.

d. Appendix D - Bibliography. This appendix provides references and sources of information presented throughout the ETL.

e. Appendix E- Design Examples. This appendix presents design examples for Landfill Off-Gas Collection and Treatment.

5. Action. Each U.S. Army Corps of Engineers design element will be responsible for incorporating guidance into HTRW or military construction designs. This ETL will be considered as the design guidance for the installation of Landfill Off-Gas collection, treatment and monitoring systems.

6. Implementation. This information is furnished to assist designers in design of new and/or retrofit facilities to convey and treat off-gas from municipal and industrial landfills. Information presented herein supplements TM 5-814-5 Sanitary Landfill with information specific to gas collection and control. Use of the ETL is not limited to HTRW, Civil Works or Military Construction.

FOR THE DIRECTOR OF MILITARY PROGRAMS:

CARY JONES, P.E.
Chief, Environmental
Restoration Division
Directorate of
Military Programs

5 Appendices
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APPENDIX A
LANDFILL OFF-GAB SYSTEMS ENGINEERING TECHNICAL LETTER DESIGN CONSIDERATIONS

1.0 INTRODUCTION

Landfill gas (LFG) that is generated from the decomposition of municipal solid waste (MSW) in a landfill consists of a mix of approximately 50 percent methane (CH_4) and 50 percent carbon dioxide ($C0_2$). Trace amounts of oxygen (O_2), nonmethane organic compounds (NMOC) whose principal components are hydrogen sulfide (H_2S), and reactive organic gases (ROGs) may also be present.

There are increasing concerns with the emissions of LFG and its contribution to air pollution since volatile emissions from landfills represent a major source of organic contaminants entering the atmosphere. The concerns are based on the following:

- CH_4 gas is highly combustible, making it a potential hazard in the landfill environment, or in structures on adjacent properties;
- LFG is capable of migrating significant distances through soil, thereby increasing the risk of explosion and exposure. Serious accidents resulting in injury, loss of life and extensive property damage may occur where landfill conditions favor gas migration;
- As LFG is produced, the pressure gradient upward may create cracks and disrupt the geomembrane in the landfill cover;
- CH_4 gas is an asphyxiant to humans and animals in high concentrations;
- Migrating gas may result in other adverse effects such as stress to vegetation, by lowering the 02 content of soil gas available in the root zone;
- Gas generated at landfills and vented to the atmosphere frequently emanates nuisance odors causing annoyance to individuals residing nearby;

- Emissions of NMOC and ROG, or ozone precursors contained in LFG, may be contributing to the degradation of local air quality. Where landfills contain sources of sulfur, such as shredded construction/demolition material and gypsum board, there is increased potential for liberation of H_2S which is noxious at low concentrations and can cause asphyxiation, if gas is migrating to enclosed areas;

- Vinyl chloride from landfills has been found to be present in substantial concentrations in LFGs and has been detected in off-site conduits, representing health and safety concerns. Vinyl chloride is found in municipal as well as commercial solid waste landfills;

- CH_4 gas, one of the "green house gases", contributes to the possibility of global warming of the earth's climate; and

- Uncontrolled LFG is a loss of potential resources; instead it can be a satisfactory fuel for a wide variety of applications. Many types of energy equipment designed for conventional fuels can operate on LFG with the power output reduced about 5 to 20 percent (1)

Currently, federal and state environmental agencies are developing stringent regulations for air emissions from municipal and industrial landfills. The United States Environmental Protection Agency (EPA) has proposed regulations for control of air emissions from MSW landfills, based on Section 111 the Clean Air Act (CAA)(2). The new regulations require gas management systems as a component of the landfill final cover.

1.1 PURPOSE

The purpose of this Engineering Technical Letter (ETL) is to provide information and procedures necessary for the design of systems to monitor, collect, characterize, transport, and treat off-gas from municipal, industrial and hazardous waste landfills. The ETL describes and evaluates various LFG emission control techniques and presents design procedures relative to specific functional requirements. The ETL is intended to aid the designer and others who possess some knowledge of hydrogeology, civil engineering, chemistry, mathematics, materials science, and who have some design experience to select the most effective solutions to problems of controlling LFG.

1.2 SCOPE

The following topics are discussed in this ETL:

- Chapter 1, Introduction, presents the origin of LFG, reasons why control is necessary, the purpose of this ETL, the scope of this ETL, and LFG control issues;
- Chapter 2, Theory of Landfill Gas Emissions, discusses the mechanisms of LFG generation, factors affecting LFG generation, transport mechanisms, and factors affecting LFG movement/migration, LFG characteristics, condensate characteristics, mathematical gas flow, estimation of LFG production, and different LFG estimation models;
- Chapter 3, Landfill Off-gas Applicability, discusses LFG collection, LFG disposal and treatment for energy recovery, along with advantages and disadvantages of each technology;
- Chapter 4, Design Considerations, discusses design parameters of LFG collection systems, LFG treatment systems, LFG condensate treatment methods, LFG purification systems, gas measurement systems, instrumentation, monitoring, control, and utility requirements;

- Chapter 5, Regulatory Requirements, discusses current and proposed regulations applicable to air toxic rules under the CAA, local air toxic rules, and proposed global warming legislation;

- Chapter 6, Environmental Issues, discusses adverse effects of LFG emissions and benefits of LFG control;

- Chapter 7, Construction Materials and Installation, discusses construction materials for gas collection systems, treatment equipment, condensate collection and treatment systems, construction criteria and quality assurance (QA) guidance;

- Chapter 8, Operating Conditions, discusses operation safety, process interferences, operation concerns, system start-up, training, maintenance requirements, and operation labor requirements;

- Chapter 9, Design and Construction Package, discusses design analysis, design documents, drawings and specifications for bidding and construction, guide specifications, and operations and maintenance; and

- Appendices present design calculations, a check list for design documents, bibliography, design examples and definitions of terms and acronyms.

1.3 REFERENCES

The information used in the development of this ETL is listed in Appendix D, Bibliography.

1.4 BACKGROUND

Sanitary landfilling is the primary method for disposal of municipal and household solid waste or refuse in the United States (U.S.). The daily per capita quantity of solid waste generated for military troop facilities is estimated at 2 to 3 kgs (4 to 6 lbs) of combined refuse and garbage (3) . Hazardous waste amounts vary with the locations and military activities. Based on the effective population of 5000, which is the sum of the resident population and non-resident employees at a typical military base, the amount of solid waste or refuse landfilled annually by each base is about 5,000 tons. The quantity and quality of LFG generated in a landfill depends on the types of solid wastes that are decomposing. LFG is produced at a volume of approximately 3 to 6 cubic feet per pound of municipal solid waste (2).

Experience with landfill-generated CH_4 recovery and utilization has shown that installation of LFG collection systems has reduced LFG emissions and improved local air quality. LFG is being increasingly developed as an energy resource and is currently recovered commercially at more than 70 sites in the U.S. and a number of sites in the United Kingdom and Europe (1).

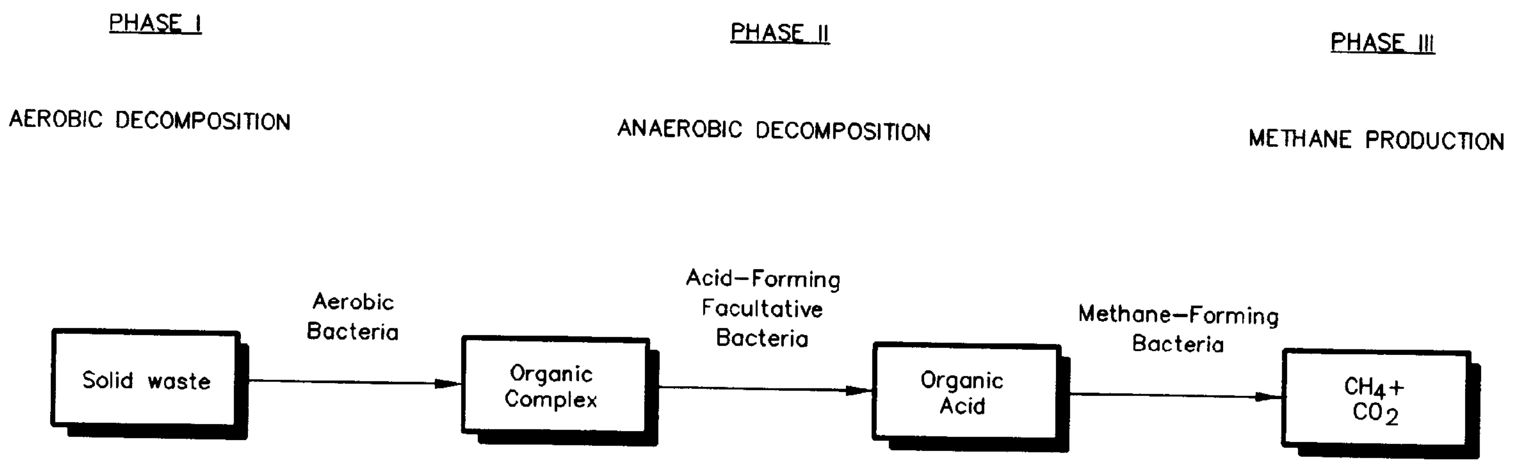
1.5 THEORY

A landfill can be described as an engineered burial of solid wastes that are subsequently degraded by chemical reactions and biological activities. The biological degradation or decomposition of solid wastes generates CH_4, and $C0_2$ along with traces of other compounds. The biological decomposition of solid waste follows three distinct phases, as illustrated in Figure A-1.

Phase 1. The microorganisms slowly degrade the complex organic portions of the waste using the O_2 trapped during the landfilling process to form simpler organic compounds, $C0_2$ and water. This phase is termed aerobic decomposition.

Phase 2. After the O_2 is fully consumed, facultative bacteria grow and decompose waste into simpler molecules such as hydrogen, ammonia, $C0_2$, and organic acids. This second phase is step one of the anaerobic phase.

Phase 3. In the third decomposition phase (step two of anaerobic phase), CH_4-forming bacteria (methanotrops) utilize $C0_2$, hydrogen, and inorganic acids to form CH_4 gas and other products.



THREE-STAGE BIOLOGICAL DECOMPOSITION OF SOLID WASTE

FIGURE A-1

Chemical reactions between wastes placed in landfills may also take place producing volatile constituents.

1.6 OBJECTIVES

The overall objective of this ETL is to aid in the design of LFG control systems; i.e., extraction, disposal, treatment and utilization of LFG for energy recovery.

Sub-objectives include:

- Review and analyze available knowledge of the LFG-generation process; estimate production rate, and specific characteristics that influence the production rate;
- Examine and analyze alternative collection, monitoring, treatment, processing, and utilization methods of LFG to achieve economic viability;
- Review and evaluate the landfill off-gas design and operation techniques including condensate management to aid in selecting an optimum system design for a specific site; and
- Provide design examples for guidance.

2.0 THEORY OF LFG EMISSIONS

LFG emissions are primarily governed by the following variables:

- gas-generation mechanisms,
- factors influencing gas generation,
- gas-transport mechanisms, and
- factors influencing gas transport.

The following sections discuss these issues.

2.1 GAS-GENERATION MECHANISMS

LFG is produced from one or more of three mechanisms:

- evaporization/volatilization,
- biological decomposition, and
- chemical reactions.

Physical, chemical, and biological processes transform solid waste after it is deposited in a landfill. The waste is first compressed by landfill equipment, and subsequently compacted by more waste and daily cover materials. In addition to the initial compression and compaction, the landfill undergoes settlement for many years. This settlement occurs as the waste further consolidates and biological decomposition reduces the waste volume. The landfill's final waste thickness may be reduced by as much as 30 percent due to settlement.

Water infiltration through the cover material, percolation of water contained within the original waste, and water produced as a product of waste decomposition, all form a medium in which soluble substances dissolve and generate leachate. Chemical and biochemical reactions within the landfill mainly involve the products of the decomposing waste, hydrogen, organic acids, CH_4, and CO_2.

2.1.1 Evaporation/Volatilization

Vaporization action is due to the change of chemical phase equilibrium that exists within the landfill. Some gas-generating materials will be present in the waste mass as it is received and deposited in the landfill. Organic compounds in the landfill cells will vaporize until the equilibrium vapor concentration is reached. This process is accelerated when the waste becomes biologically active, as a result of heat, which is evolved within the landfill as part of the biological process. The rate at which components are evolved depends on physical and chemical properties of the compounds. The most significant of these parameters are the Henry's Law Constant, which describes the equilibrium partitioning between the vapor and aqueous phases at a given pressure and temperature.

Henry's Law Constant. Henry's Law determines the extent of volatilization of a contaminant dissolved in water.

Henry's Law states: The weight 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 following formula:

$$P_A = H_A * X_A \tag{2-1}$$

where,

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

Henry's constant quantifies the tendency for a liquid compound in solution (i.e., in groundwater or soil moisture) to partition to the vapor phase. This constant is temperature-dependent, increasing with an increase in temperature. In general, liquid compounds with Henry's constants greater than 10^{-3} atm.m^3/mol are considered to have high vapor-phase partitions. When using Henry's constant for various compounds, care must be taken to use a consistent system of units. The table below summarizes the various forms of Henry's constant and appropriate units:

Units and Conversion Factors for Henry's Constant

P Concentration in Gas Phase	X Concentration in Liquid Phase	Henry's Constant	
		Symbol	Units
atm	mol fraction	H_C	atm
atm	mol/m^3	H	$atm\text{-}m^3/gmol$
g/m^3	g/m^3	$H_{A'}$	dimensionless
mol fraction	mol fraction	$H_{A'}$	dimensionless

Conversion factors for Henry's Constants

1. H = (VP * MW)/S

where,

H = Henry's Constant, $atm\text{-}m^3/gmol$
VP = vapor pressure of pure substance, atm
MW = Molecular weight, g/gmol
S = Solubility of gas, g/m_3

2. $H_C = H * C_0$

where,

H_C = Henry's Constant, atm
C_0 = Molar Density of Water, $55.6x10^3 gmol/m^3$
or 55.6 $kmol/m_3$
or 55.6 gmol/L

3. $H_{A'} = H_C/(C_0*R*T)$

where,

$H_{A'}$ = Henry's Constant, dimensionless
R = Universal Gas Constant, $8.2x10^{-5} atm\text{-}m^3/gmol\text{-}T$
T = degrees Kelvin

Estimated Henry*s constants for some organics at 20°C (68°F) are shown in Table A-1.

2.1.2 Biological Decomposition

Sanitary landfills produce large quantities of gas, with the major component being CH_4. LFG generation occurs as a result of two conditions, aerobic and anaerobic decomposition. Generally, aerobic conditions degrade the larger molecules into

TABLE A-1

Henry's Constant of Common Organic Compounds

Compounds	H atm.m^3/gmol	H_C atm	H_A' Dimensionless
Vinyl chloride	6.4	3.56×10^5	266
Dichlorofluoromethane	2.1	1.17×10^5	87.6
Methane	0.63	3.50×10^4	26.2
1,1-Dichloroethylene	1.7×10^{-1}	9.45×10^3	7.07
1,2-Dichloroethylene	1.7×10^{-1}	9.45×10^3	7.07
Chloroethane	1.5×10^{-2}	8.34×10^2	0.62
Trichloroethylene	1.0×10^{-2}	5.56×10^2	0.42
1,1,1-Trichloroethane	3.6×10^{-3}	2.00×10^2	0.15
Chloroform	3.4×10^{-3}	1.89×10^2	0.14
Methylene chloride	2.5×10^{-3}	1.39×10^2	0.10
1,1,2-Trichloroethane	7.8×10^{-4}	$4.34. \times 10^1$	0.032
Naphthalene	3.6×10^{-4}	2.00×10^1	0.014
Phenol	2.7×10^{-4}	1.50×10^1	0.0011

Source: Adapted from Reference 4

smaller and smaller molecules leading to anaerobic degradation of organic acids which generates CH_4 and $C0_2$. It is important to understand that there will be mixed aerobic and anaerobic degradation occurring at the same time. The facultative, degrading microbes (capable of growing and surviving with or without 0_2) perform the necessary dual functions of degrading larger molecules and consuming O_2 to create and sustain the anaerobic environment which favors CH_4 production.

These processes normally occur in three stages: aerobic, anaerobic/thermophilic, and anaerobic/methanogenic. The bacteria involved in biological decomposition exist in the refuse and soil used in landfill operations. Seeding the refuse with bacteria from another source can result in a faster rate of development of the bacterial population.

The gas release rate into the waste void space is principally affected by the pH and the rate of water production in each of the modes of bioprocessing. Since water is a normal product of the first stage (aerobic), more water may be present in the matrix than would normally be expected based on the water content of the wastes. This water will compete for space with the air during compaction and will dissolve some of the bioreaction gases. The first two stages reduce the pH of the water and may affect the evaporation/volatilization rate accordingly.

2.1.3 <u>Aerobic Decomposition</u>

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. Decomposition products under aerobic conditions are $C0_2$ (primarily), water, and nitrate. Aerobic bacteria produce a gas characterized by high temperatures (54 to 7l°C or 130 to 160^{0}F), high $C0_2$ content (30 percent), and low CH_4 content (2 to 5 percent).

Aerobic decomposition may last for as little as 6 months to as long as 18 months for waste in the bottom lifts of the landfill. However, in the upper lifts of the landfill, aerobic decomposition may last for as little as 3 to 6 months if CH_4-rich gas from lower lifts flushes 0_2 from the voids in the upper lifts. Aerobic decomposition produces the conditions and byproducts necessary for anaerobic decomposition. Limited aerobic decomposition from infiltration of 0_2, as air or dissolved in water, into the landfill may continue for years. This continuing okidative degradation by aerobic and facultative organisms can continue to drive the subsequent anaerobic processes. Aerobic degradation generally degrades many of the larger polymers in the wastes, such as starches, cellulose, lignins, proteins, and fats into smaller, more available oligomers (polymer consisting of 2 to 4 monomers) which can then be further degraded into dimers (molecule consisting of two identical simpler molecules) and monomers such as sugars, peptides, amino acids, long-chain fatty acids, glycerol and eventually organic acids, as discussed below. These less complex products of aerobic degradation are more readily degraded anaerobically than the larger polymers.

2.1.3.1 <u>Anaerobic Decomposition</u>

Anaerobic decomposition occurs in two distinct processes. When all of the entrained **O~** is depleted from the waste, the waste decomposition changes from aerobic to anaerobic, and two new groups of bacteria emerge which thrive in anaerobic (no O_2) environments. Facultative microbes convert the simple monomers into mixed acid products along with hydrogen and $C0_2$. 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, using water in place of O_2. These organic acids reduce the pH, which increases the solubilization of some organic and inorganic wastes, thereby 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 the methanogenic (methane-producing) bacteria. During the second anaerobic process, the methanogenic bacteria become more prominent. These methanogens degrade the volatile acids, primarily acetic acid and use the hydrogen to generate CH_4 and $C0_2$ (typically in a 1:1 ratio). This degradation results in a more neutral pH (7 to 8), a decrease in the COD, and a decrease in the conductivity, as the organic acids are consumed.

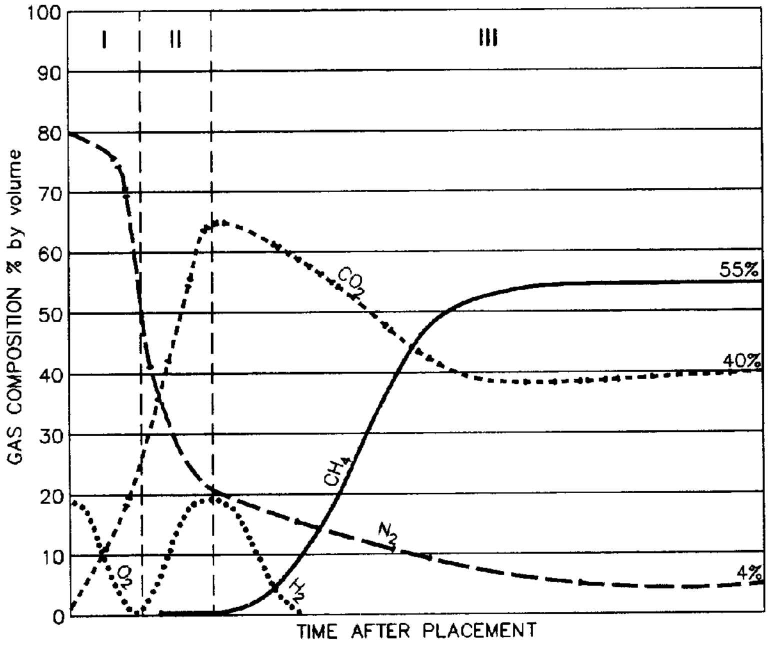
The resulting anaerobic decomposition is characterized by lower temperatures (38 to 54°C or 100 to 130°F), lower $C0_2$ concentrations (40 to 48 percent), and significantly higher CH_4 concentrations (45 to 57 percent) than the generally aerobic phase of decomposition. Anaerobic decomposition will continue until all of the volatile organic acids are depleted or until O_2 is reintroduced into the waste, stimulating a resumption of aerobic decomposition of the remaining large polymeric materials and a new degradation cycle. Reverting to aerobic conditions temporarily retards CH_4 gas generation.

Figure A-2 illustrates the evolution of LFG by biological processes.

2.1.4 Chemical Reactions

Chemical reactions between materials in the waste can release gases. Such reactions are likely to occur in hazardous waste landfills unless considerable care is taken not to mix incompatible materials. Older landfills which have received hazardous wastes in the past and municipal landfills which receive household waste are still subject to unforeseen reactions. For example, aliphatic chlorinated solvents are incompatible with aluminum, so solvent-soaked rags which contact aluminum cans may produce hydrogen chloride gas. This will at least render the surrounding gas highly acidic, and may release some vapor through the landfill to the atmosphere.

Many of the potential reaction problems are relatively buffered by the presence of water. Even some materials which are vapors in their pure state (e.g., vinyl chloride) are relatively soluble in water, so the release rate is dampened. However, unpredictable reactions are possible with so many compounds potentially present. As mentioned above, the heat generated from biological processes also tends to accelerate the release rate of compounds produced by chemical reactions.



TYPICAL LANDFILL GAS EVOLUTION

FIGURE A-2
(SOURCE 5)

2.2 FACTORS AFFECTING LFG GENERATION

Gas generation in a landfill is affected by several factors:

- availability of nutrients,
- temperature,
- moisture,
- pH,
- atmospheric conditions,
- age of waste, and
- variation of water table.

These parameters are discussed below.

2.2.1 Availability of Nutrients

Bacteria in a landfill require various nutrients for growth; primary carbon, hydrogen, O_2, nitrogen, and phosphorous (macronutrients), but also require small amounts of other elements such as sodium, potassium, sulfur, calcium and magnesium (micronutrients). The availability of macronutrients in the landfill mass has an effect on both the volume of water generated from microbial processes and the composition of the generated gases. Landfills which accept municipal wastes and use daily soil cover will, in general, have an adequate nutrient supply for most microbial processes to proceed. Specialized landfills such as those in military installations which handle hazardous materials or munitions wastes only, and which do not use daily soil cover, may not have sufficient nutrients in the waste to sustain a microbial population. Once the microbial processes are established, nutrients are regenerated from sloughing processes as bacteria die. The primary sources of macronutrients are green wastes, food wastes and soil cover, but will always be limiting if not supplemented from an outside source. Some loss of nutrients can occur as LFG components. The supply of micronutrients (primarily metals) is less certain, but evidence from hundreds of landfills suggests that municipal landfills also contain adequate supplies. The sources of these micronutrients are usually the trace elements found in almost all soils and many wastes. The micronutrient requirements are very small and can usually be met by these trace amounts in the wastes and leached from the soil cover.

If the nutrient supply is rich, the population of active microbes may become so high that they crowd the available pore spaces and restrict both water flow and LFG flow temporarily. In general, the situation will correct itself because the limited transport will cause some of the bacteria to die of starvation. Nutrient availability can be improved by the addition of sewage sludge, manure or agricultural wastes.

2.2.2 Temperature

Temperature conditions within a landfill influence the type of bacteria that are predominant and the level of gas production. The temperature of the landfill may vary dramatically from one section to another, as the temperature of the material is affected by several factors. The primary factors of temperature variations are depth, compacted density, temperature of the surrounding area, microbial or other chemical activity, water content and climate. Warm landfill temperatures favor CH_4 production; a dramatic drop in activity has been noted at temperatures below 10°C (50°F). The optimum temperature range for aerobic decomposition is 54 to 71°C (130 to 160°F), while the optimum temperature range for anaerobic bacteria is 30 to 41°C (85 to l05°F). Landfill temperatures are reported to be typically in the range of 29.5 to 60°C (85 to 140°F) as result of aerobic decomposition, but may be expected to drop to the 19 to 21°C (65 to 75°F) range as result of anaerobic activity. The temperature needs to be measured in several locations and an estimate made of the temperature likely to occur in the gas generation zone of interest for design purposes.

2.2.3 Moisture

Moisture content is considered the most important parameter regarding refuse decomposition and gas production. A high moisture content of the waste (between 50 percent and 60 percent) by weight favors maximum CH_4 generation(5). This is contrary to standard landfill applications, where the waste is maintained as dry as possible in order to minimize leachate production. The moisture content of MSW as received typically ranges from a low of 15 to 20 percent to a high of 30 to 40 percent with an average of 25 percent on a wet weight basis. The moisture content can vary greatly in different zones of the landfill. Very low moisture content, such as the case of solid waste in arid regions, may prevent decomposition of waste and thus limit gas production. Leachate recirculation (if allowed) would permit control of the moisture inside the landfill. Typically, when a waste achieves a 50 percent moisture (on a wet basis) it has reached the field capacity, and will tend to leach continuously downward thereafter for additional moisture added. In-situ moisture content as high as 70 percent is possible. At this level, a decrease in the efficiency of a gas collection system can be expected.

2.2.4 pH

The solid material placed in a landfill can vary widely in pH, but usually the average value for municipal waste will be between 5 to 9 standard units. The pH of hazardous wastes can vary widely, and known acids or bases are usually neutralized prior to landfilling. The pH in an active landfill becomes governed primarily by the biological processes described in Section 2.1.

The pH during CH_4 formation is in the range of 6.5 to 8.0, but the optimum pH of CH_4 fermentation is in the neutral to slightly alkaline range (7.0 to 7.2)(7). Most landfills have an acidic environment initially, but when the aerobic and acidic anaerobic stages have been completed, the methanogenic processes return the pH to approximately neutral (7 to 8) due to the buffering capacity of the system pH and alkalinity.

One concern during the acidic stages of the biological process is that the reduced pH will mobilize metals which may leach out of the landfill, or become toxic to the bacteria generating the gas. This is of particular concern where it is known that heavy metals are being placed in the landfill in large quantities. Enhancement of gas production can be achieved by carefully screening the types and amounts of wastes admitted to the landfill; i.e., exclusion of toxic or inhibitory materials, and size reduction of refuse materials. In some cases, the addition of sewage sludge, manure or agricultural wastes during refuse placement would improve CH_4 gas generation.

Military landfills are not generally producing a great quantity of CH_4 gas. Therefore, enhancement of CH_4 gas production is usually not practiced; the gas collection system is designed primarily to prevent the release of gases to comply with the state regulations.

2.2.5 Atmospheric Conditions

The atmosphere affects the conditions in the landfill in three ways: temperature, barometric pressure and precipitation.

In a landfill where soils are used for cover layer, the air temperature not only affects the surface layer of the waste but may have an impact into the deeper layers, because the air permeability will generally be higher in the landfill. Cold climates will reduce biological activity in the surface layers, reducing the volume of gas generated. Deeper in the wastes, the surface temperature effects are often overcome by the heat generated by bacterial activities.

The atmospheric pressure influence is also stronger than would occur in soil systems, where the normal surface air interaction with the soil extends about 6 inches. Until the waste is consolidated to a typical soil density, the barometric pressure can affect the wastes near the surface by drawing air in or venting gas out of the top layer. Wind will also affect the diffusion rate deeper in the landfill by reducing the surface concentration of gas components and creating advection near the surface.

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. As the water percolates through the waste, it also extracts materials such as organics or metals as described above. High rates of precipitation may also flood sections of the landfill, which will obstruct gas flow.

In a landfill where geomembrane is used for final cover, the geomenbrane will isolate the waste and minimize many of the atmospheric effects described above.

2.2.6 Age of Waste

The three stages of biological degradation discussed in Chapter 2 have a primary influence on the gas generation rate. During the aerobic phase, the waste is close to the surface and the generated gas is difficult to capture. Aerobic metabolism is oxidative and generally more complete and rapid than anaerobic processes, so the initial rate of $C0_2$ production is relatively high. As the waste becomes depleted in O_2 and the acidic processes dominate, the LFG production rate decreases. When the acids have been consumed and the methanogens become dominant, the LFG production rate rises again through a peak and then stabilizes. The ideal time to start collecting LFG is at the beginning of site closure. This usually represents the maximum gas generation point, and gas quantities should remain significant for as long as a 10 years. After the landfill closes, the gas generation rate decreases as the organic substrate is consumed and not replaced. It may take as long as 50 years, however, for gas production to cease.

2.2.7 Variation of Water Table

The local geology which will affect the gas-generation rate is the depth and seasonal variation of the water table. Landfills are almost always designed to exist completely above the local water table; if the seasonal high water reaches the bottom of the fill, the hydraulic pressure will affect the waste, and LFG production, in several ways:

- The pressure gradient may lift a liner system and rupture the liner, permitting air and water to penetrate the waste pack;

- Air movement will be stopped in any saturated zone which may be created in the waste;

- Biological activity may stop, change form as oxygenated water is introduced, or be enhanced by the presence of "fresh" water in the leachate; or

- Rupture in the liner may permit leachate to drain from the fill as the water table lowers after reaching its high point.

2.3 TRANSPORT MECHANISMS

The nature of the specific transport mechanism depends on the type of waste (solid or liquid) exposed to the atmosphere. For liquids, the principal release mechanism will be governed by Henry's Law for dilute aqueous solutions. Each compound present has a different constant describing the equilibrium partitioning between the solution and the vapor phase. Many of the volatile organic compounds (VOCs) which may be present (see Table A-1) have high Henry's Law constants; they would preferentially migrate to the vapor phase and out of the landfill. During the landfilling process, this migration is accelerated by the effects of mixing, because the liquid surface (even in a solid matrix) is exposed to the ambient air more frequently.

Several physical mechanisms describe the behavior of volatile compounds as they may be released into the atmosphere from a landfill. The transport may occur by the three principal mechanisms:

- molecular effusion,
- diffusion, and
- convection.

These transport mechanisms are discussed below.

2.3.1 Molecular Effusion

Molecular effusion occurs at the surface boundary of the landfill with the atmosphere. When the material has been compacted, and not has been covered, effusion is the process by which diffused gas releases from the top of the landfill.

For dry solids, the principal release mechanism is direct exposure of the waste vapor phase to the ambient atmosphere. Any volatile liquid constituents which coat the soil surface would be released according to Raoult's Law, which predicts the release rate based on the vapor pressure of the compounds present. Essentially the constant in Raoult's Law describes the partition coefficient between a pure liquid compound and its vapor phase.

Raoult's Law. The vapor-pressure depression of a constituent is directly proportional to the concentration of particles in solution. In other words, the partial vapor pressure of a constituent in a gaseous mixture is equal to the mole fraction of that constituent in the solution times the vapor pressure of the pure constituent i, which is a function of temperature. Raoult's Law is presented by the following formula:

$$P_v = X_i * P_o \qquad (2\text{-}2)$$

where,

P_v = partial pressure of a compound in gaseous mixture, atm
X_i = concentration of compound in solution, mole fraction
P_o = vapor pressure of the compound in pure state, atm

Vapor Pressure. 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 a given compound is the single most significant factor affecting the performance of an off-gas collection system. The vapor pressure of water at 20°(68°F) is .34 KN/m^2(0.399 psi). In general, compounds which exhibit vapor pressure greater than 0.5 mm Hg (0.27 in. H_2O) are appropriate for off-gas collection. Conversion units of the pressure are given below:

1 newton = 0.2248 pounds
1 pound = 231 cm of water column (at 4°C)
1 mm Hg = 0.5353 inches of water (at 4°C)
10^5 newton/m^2 = 100 KPa

One physical effect on the release rate from the surface is wind speed. As discussed in Section 2.3.2, wind serves to keep the ambient concentration at or near zero, which creates a concentration gradient for material to migrate to the surface.

Wind is also the dispersion mechanism to move the constituents into the surrounding area.

2.3.2 Diffusion

Molecular diffusion occurs in gas systems when a concentration difference exists between two different locations within the gas. 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 a lower concentration area (the ambient air). Wind often serves to keep the surface concentration at or near zero, which renews the concentration gradient between the surface and the landfill on a continuing basis and thus promotes the migration of vapors to the surface. Geomembrane caps on landfills will have a significant effect on diffusion, because the geomembranes isolate the transport mechanism between the surrounding atmosphere and the landfill.

The rate of diffusion is affected by the vapor density, but the concentration gradient will tend to overcome small differences in density. Specific compounds exhibit different diffusion coefficients, which are the rate constants for this transport.

The published diffusion coefficients have been calculated using open paths between one vapor region (concentration) and another, which is not the case for landfills. The trapped gas must travel a tortuous path to reach the surface because it must travel around all the solids and liquids in its path; thus, the published diffusion coefficients for the constituents must be used with care in detailed design work. They serve more as relative indicators, and are one contributing factor to the monitoring and modeling described in Sections 2.7 and 4.7.

2.3.3 Convection

Convective flow occurs where a pressure gradient exists between the landfill and the atmosphere; gas will flow from higher pressure to lower pressure regions, and also a flow from the landfill to the atmosphere. Where it occurs, convective flow of gas will overwhelm the other two release mechanisms in its ability to release materials into the atmosphere. The source of the pressure may be the production of vapors from biodegradation processes, chemical reactions within the landfill, compaction effects, or CH_4 generation at the lower regions of the landfill which drive vapors toward the surface. Variations in water table elevations can also create small pressure gradients which either push material out (rising tide) or draw material in (falling tide). Even changes in barometric pressure at the surface can have an impact on the convective flow of gas. The rate of gas movement is generally orders of magnitude faster for convection than for diffusion. For a particular gas, convective and diffusive flow may be in opposing directions, resulting in an overall tendency toward cancellation. However, for most cases of LFG gas recovery, diffusive and convective flows occur in the same direction. Figure A-3 illustrates the transport mechanisms.

2.4 FACTORS AFFECTING LFG TRANSPORT MECHANISMS

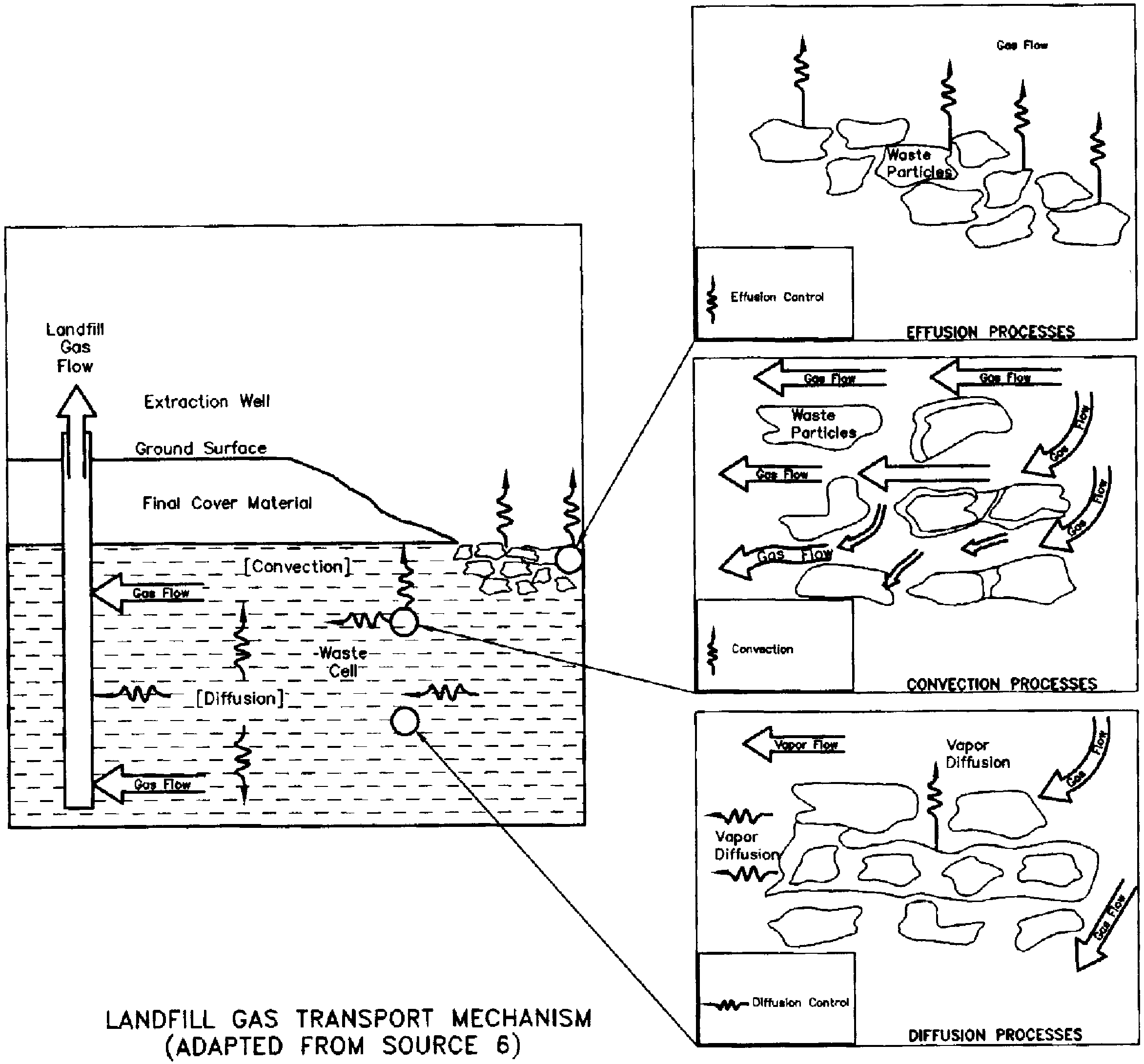
LFG transport is affected by the following factors:

- permeability,
- depth of groundwater,
- condition within the waste,
- moisture content,
- man-made features, and landfill liner and cap systems.

2.4.1 Permeability or Intrinsic Permeability

A coefficient of permeability, k, is often used to describe the rate of discharge of the fluid (liquid or gas) under laminar-flow (non-turbulent) conditions and at a standard temperature (usually 20°C or 68°F) through a unit cross-sectional area of a porous medium under a unit hydraulic gradient. The LFG permeability is a function of both its intrinsic (k_i) and relative (k_r) permeabilities.

The intrinsic permeability coefficient, k_i, is a measure of the ease with which a porous medium can transmit LFG, water, or other fluid through its media. The intrinsic permeability is specific for each landfill, and is a function only of the porous medium. The dimensions, in length squared, may be expressed in



LANDFILL GAS TRANSPORT MECHANISM
(ADAPTED FROM SOURCE 6)
FIG. A-3

units of darcies: 1 darcy = $9.87 \times 10^{-9} cm^2$. The permeability coefficient reported for Palos Verdes Landfill is 20 darcies (5).

The relative permeability is a dimensionless number and is expressed as a fraction of the maximum permeability value that the medium can exhibit for a given fluid. Gas permeability can be measured or estimated by a variety of methods, one of which is presented in Section 4.2.5.5.

The permeability distribution to gas has a profound influence on gas flow rates and gas recovery rates. Coarse-grain refuses typically exhibit large values of gas permeability and more uniform gas flow patterns. Both of these factors tend to promote increased LFG recovery rates. By contrast, fine-grained refuses are characterized by small values of gas permeability and gas flow patterns which are primarily restricted to macropores or secondary permeability zone such as fractures.

2.4.2 Depth of Groundwater

The water table surface tends to act as a no-flow boundary for gas flow within the unsaturated zone. As a result, it is generally used to estimate the thickness of the zone from which a gas can be moved.

The depth to groundwater as well as seasonal variations need to be evaluated during the predesign process to evaluate the well construction requirements as well as the potential for water table upwelling (i.e., the upward rise of the water table toward a vacuum well screened in the unsaturated zone). The potential rise in the water table that can occur at a location is expressed as an equivalent water column height (in cm H_20). The limit of upwelling, z (cm) can thus be calculated as:

$$h_{rise} = 1033(1-P_r) \qquad (2\text{-}3)$$

where,

h_{rise} = increase in the water table surface, cm of water

P_r = pressure reading as a function of the radial distance from the vertical extraction well, atm

1033 = conversion from 1 cm of water vacuum pressure to 1 atmosphere.

Upwelling is not a significant concern in more permeable formations, as the applied vacuum will have little influence. In less permeable formations, however, upwelling can be significant and should be quantified for efficient gas system design and operation.

2.4.3 Conditions Within the Waste

The distribution and occurrence of waste and debris within the unsaturated zone greatly affects gas migration and recovery rates. The conditions within the waste (solid matrix) which may affect soil gas transport include:

Heterogeneities. Heterogeneities are caused by spatial variations in solid matrix type, layering, unusual refuse composition and moisture content. Due to the heterogeneous nature of the landfill environment, there will be some acid-phase anaerobic decomposition and some aerobic decomposition occurring simultaneously in any large-scale landfill, along with the methanogenic decomposition. During the operation of an off-gas collection system, these variations may influence LFG quality, gas flow patterns and ultimately gas recovery rates within the landfill.

Porosity. Landfill solid waste's porosity (n) is a ratio of the void volume to the total volume of the porous medium, usually expressed as a decimal fraction or percent. Waste pores can be expressed as a decimal fraction or percent. Waste pores can be occupied by gas, water, and/or bacteria. Porosity can be calculated from the bulk density of the waste, which is the dry weight of waste per bulk volume (i.e.,by following formula:

$$n = 1 - (D_b / D_s) \qquad (2\text{-}4)$$

where,

n = waste porosity, dimensionless
D_b = bulk density of the waste, kg/m^3
D_s = density of the particle, kg/m^3

The waste porosity of the landfill ranges between 0.04 to 0.10.

The effective porosity is a measure of a waste's ability to transmit air. The effective porosity provides a more useful measure of the rate at which gas is recovered compared to porosity, however. The effective porosity must be quantified in the laboratory and results may be difficult to reproduce. An indirect measure of the effective porosity can be performed during air-phase permeability pilot testing, if conducted.

Moisture Retention. The moisture content of the solid matrix influences the magnitude of the air phase permeability. Water competes with air to occupy pore space within the solid matrix and ultimately reduces the ability of vapors to migrate through the landfill due to a reduction in the air pathway. This reduction may decrease gas recovery rates.

2.4.4 Man-Made Features

In some instances, underground utilities such as storm and sanitary sewers or the backfill material associated with these features may produce short circuiting of air flow associated with an off-gas collection system. As a result, air flow may be concentrated along these features rather than within the zone requiring collection. In addition, these features may also provide migration pathways for both free-phase liquids and vapors within the unsaturated zone. As a result, the orientation and geometry of these features may dictate the direction in which the liquids or vapors migrate.

2.4.5 Landfill Cap and Liner Systems

The components of a hazardous waste landfill cap generally consist of a top layer composed of a vegetated or armored surface component and select fill, a drainage layer, low permeability layer composed of a geomembrane over a low permeability soil component, and a random fill layer overlaying the waste. In addition to the benefit which landfill caps provide for the final closure of landfills, they also provide a significant improvement to the LFG collection by allowing maximum recovery of LFG from all portions of the landfill via elimination of the need for an exclusion of few feet from cover (buffer zone).

In active collection systems, whether with vertical or horizontal collectors, a geomembrane cap will preclude the intrusion of any air into the refuse. Higher operating vacuum can, therefore, be applied to the gas collection system without danger of overdrawing the gas. Thus the effective radius (reach) of influence of each well is increased.

Landfill liners consist of natural low permeability geologic formations, recompacted clay liners, geomembranes, and geosynthetic clay liners. In addition to prevent the migration of LFG to the surrounding areas, the significance of liners with respect to the LFG collection is to prevent groundwater and/or other gases from the subsurface from being pulled into the LFG collection system.

2.5 CHARACTERISTICS OF LFG

The characteristics of LFG include:

- physical characteristics, and
- chemical characteristics.

These characteristics are discussed below:

2.5.1 Physical Characteristics

Physical characteristics include:

- density,
- viscosity,
- temperature,
- heat value content, and
- moisture content.

Density. The density of LFG depends on the proportion of gas components present. For example, a mixture of 10 percent hydrogen and 90 percent CO_2, such as might be produced in the first stage of anaerobic decomposition, will be heavier than air, while a mixture of 60 percent CH_4 and 40 percent $C0_2$, such as might be produced during the methanogenic phase of decomposition, will be slightly lighter than air. Therefore, the greater the waste density the higher the theoretical yield of LFG per unit volume of void space. Density, D, has units in $kg.m^{-3}$ or $lb.ft^{-3}$. Some common values for LFG are given below:

D CH_4 = 0.714×10^{-4} kg/m^3 or $1.153 \times 10^{-3} lb.ft^{-3}$.

D Composite gas: = 1.07 kg/m^3 or $17.13 lb.ft^{-3}$

Viscosity. Viscosity of a fluid (liquid or gas) is that property which offers resistance to flow due to the existence of internal friction within the fluid. This resistance to flow, expressed as a coefficient of dynamic (or absolute) viscosity is the force required to move a unit area a unit distance.

Absolute viscosity μ is measured in units of $Newton.sec.m^{-2}$; $g.cm^{-1}.sec^{-1}$; Pascal or Newton ($lb.sec.ft^{-2}$; centipoise, or $slug.ft^{-1}.sec^{-1}$). For example, at 0°C and 1 atmosphere of pressure, approximate values of μ for CH_4 and composite gas are as follows$^{(5)}$:

μ CH_4 = 1.04×10^{-5} $N.sec.m^{-2}$ or 2.17×10^{-7} $lb.sec.ft^{-2}$
μ Composite gas: = 1.15×10^{-5} $N.sec.m^{-2}$ or
= $2.40 \times 10^{-7} lb.sec.ft^{-2}$

Temperature. Gas temperature varies with location, depth and phase decomposition. This subject is discussed in previous Section 2.2.2.

Heat Value Content. Concentrated mixtures of LFG can be expected to have a calorific value of 500 Btu/cft during the CH_4 generation (methanogenic) stage. This value is about half that of natural gas.

Moisture Content. The amount of moisture in the gas depends on the temperature and pressure and can be saturated or under-saturated. Incoming refuse has an average moisture content of about 25 percent with food and garden components of the waste providing the highest moisture input. Rainfall, surface and groundwater infiltration, and waste decomposition will provide additional moisture.

2.5.2 Chemical Characteristics.

The composition of LFG depends on the waste type and the stage of decomposition. The amount of LFG produced is generally a function of the type, extent and rate of decomposition. The major environmental conditions which affect the type, rate and extent of biochemical decomposition in a landfill are O_2 availability, moisture, rainfall infiltration, temperature, pH, amount of solid waste, and available microbes. As discussed previously, the major components of the LFG are CH_4, CO_2, NMOC and water vapor. The maximum gas yield has been estimated to be 15,000 cubic yards per ton of waste, with an average estimated gas composition by volume of 54 percent CH_4 and 46 percent CO_2 and trace amounts of NMOCs.

2.5.2.1 Methane

A major constituent of LFG is CH_4. CH_4 is lighter than air, colorless and odorless. LFG is flammable due to the presence of CH_4 and can be asphyxiant if present in high concentrations without O_2. CH_4 is explosive at about 5 to 15 percent by volume in air. The presence of CO_2 affects these ranges although little significant change occurs in the lower limit of the range.

2.5.2.2 Carbon Dioxide

Another major constituent of LFG is CO_2. CO_2 is heavier than air, colorless, and odorless. CO_2 can be a simple asphyxiant and health hazard if present in high concentrations.

2.5.2.3 Non-Methane Organic Compounds (NMOC)

Many minor constituents are present in LFG at low concentrations. Trace gases are produced by the complex interaction of the physical, chemical, and biological processes occurring within the waste. LFG contains a variety of NMOC including:

- benzene,
- toluene,
- ethylbenzene,
- vinyl chloride,
- dichloromethane,
- trichloroethylene,

- 1,2,-cis dichloroethylene, and
- tetrachloroethylene.

These compounds are widely used in industry and are found in common household products or used in their manufacture.

2.5.2.4 Water Vapor

Gas created during the decomposition of organic compounds typically includes between 4 and 7 percent by volume of water vapor. Temperatures are typically elevated over ambient during biological decomposition and increase the evaporation of water into the LFG. Water vapor content of LFG will depend on the system temperature and pressure and could be saturated under landfill conditions.

2.5.2.5 Others

Hydrogen is produced during waste decomposition, particularly during 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 in the lower limit of the range. A typical nonmethane LFG composition is presented in Table A-2.

2.6 LFG CONDENSATE

2.6.1 Source of LFG Condensate

LFG condensate accumulates in two areas:

- gas collection systems, and
- gas processing systems.

Gas condensate forms in the collection 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 material is composed principally of water, organic compounds, and traces of inorganics. Depending on the concentration of hydrocarbons, the organic compounds are generally not soluble in water and separate into aqueous and hydrocarbon phases.

TABLE A-2
Summary of Nonmethane Organic Compounds Found in Landfill Gas

Chemical Name	No. of Times Quantified	Average Conc. Detected ppm	Highest Conc. ppm	Lowest Conc. ppm
Ethane	26	252.63	1780	0
Toluene	40	59.34	758	0.2
Methylene Chloride	37	24.5	174	0
Hydrogen Sulfide	3	252.97	700	11
Ethylbenzene	31	21.73	428	0.15
Xylene	2	333.85	664	3.7
1,2 - Dimethyl Benzene	1	588	588	588
Limonene	1	470	470	470
Total Xylene Isomers	27	17.11	70.9	0
α-Pinene	1	446	446	446
Dichlorodifluoromethane	31	13.1	43.99	0
Ethylester Butanoic Acid	1	398	398	398
Propane	26	13.59	86.5	0
Tetrachloroethene	39	8.43	77	0
Vinyl Chloride	42	7.71	48.1	0
Methylester Butanoic Acid	1	305	305	305
Ethylester Acetic Acid	1	282	282	282
Propylester Butanoic Acid	1	253	253	253
1,2 - Dichloroethene	37	6.33	84.7	0
Methyl Ethyl Ketone	27	8.17	57.5	0
Thiobismethane	1	210	210	210
Methylcyclohexane	2	99.7	197	2.4
Trichloroethene	44	3.98	34	0.01
Nonane	1	167	167	167
Benzene	45	3.6	52.2	0
Ethanol	1	157	157	157
Acetone	26	5.94	32	0
2 - Butanol	1	152	152	152
Octane	1	152	152	152
Pentane	26	5.64	46.53	0
Hexane	26	5.33	25	0
Methylester Acetic Acid	1	136	136	136
1 - Methoxy - 2 Methyl Propane	1	136	136	136
2 - Butanone	1	129	129	129
1,1 - Dichloroethane	33	3.51	19.5	0

TABLE A-2
Summary of Nonmethane Organic Compounds Found in Landfill Gas

Chemical Name	No. of Times Quantified	Average Conc. Detected ppm	Highest Conc. ppm	Lowest Conc. ppm
1 - Butanol	1	100	100	100
Butane	26	3.68	32	0
4 - Methyl - 2 - Pentanone	1	89	89	89
2 - Methyl Propane	1	84	84	84
1 - Methylethylester Butanoic Acid	1	69	69	69
2 - Methyl, Methylester Propanoic Acid	1	69	69	69
Carbon Tetrachloride	37	1.85	68.3	0
Chloroethane	29	2.03	9.2	0
1,1,3 Trimethyl Cyclohexane	1	57	57	57
2 - Methyl - 1 - Propanol	1	51	51	51
1,2 - Dichloroethane	37	1.3	30.1	0
Trichlorofluoromethane	46	0.99	11.9	0
Chloromethane	30	1.38	10.22	0
2,5 Dimethyl Furan	1	41	41	41
2 - Methyl Furan	1	40	40	40
Chlorodifluoromethane	27	1.35	12.58	0
Propene	1	36	36	36
Methyl Isobutyl Ketone	26	1.38	11.5	0
Ethyl Mercaptan	3	11.93	23.8	1
Dichlorofluoromethane	28	1.2	26.11	9
1,1,1 - Trichloroethane	38	0.84	9	0
Tetrahydrofuran	1	30	30	30
Ethylester Propanoic Acid	1	26	26	26
Bromodichloromethane	29	0.71	7.85	0
Ethyl Acetate	1	20	20	20
3-Methylhexane	1	20	20	20
C10H16 Unsaturated Hydrocarbon	1	15	15	15
Methylpropane	1	12	12	12
Chlorobenzene	29	0.38	10	0
Acrylonitrile	26	0.32	7.4	0
Methylethylpropanoate	1	7.3	7.3	7.3
1,1 - Dichloroethene	32	0.23	3.1	0
Methyl Mercaptan	3	1.87	3.3	1
1,2 - Dichloropropane	28	0.12	1.8	0
1 - Propyl Mercaptan	2	1.55	2.1	1

TABLE A-2
Summary of Nonmethane Organic Compounds Found In Landfill Gas

Chemical Name	No. of Times Quantified	Average Conc. Detected ppm	Highest Conc. ppm	Lowest Conc. ppm
Chloroform	36	0.08	1.56	0
1,1,2,2 - Tetrachloroethane	28	0.1	2.35	0
1,1,2,2 - Tetrachloroethene	2	1.33	2.6	0.05
2 - Chloroethylvinyl Ether	28	0.08	2.25	0
t - Butyl Mercaptan	2	0.64	1	0.28
Dimethyl Sulfide	2	0.55	1	0.1
Dichlorotetrafluoroethane	1	1.1	1.1	1.1
Dimethyl Disulfide	2	0.55	1	0.1
Carbonyl Sulfide	1	1	1	1
1,1,2-Trichloro 1,2,2-Trifluoroethane	1	0.5	0.5	0.5
Methyl Ethyl Sulfide	1	0.32	0.32	0
1,1,2 - Trichloroethane	28	0	0.1	0
1,3 - Bromochloropropane	1	0.01	0.01	0.01
1,2 - Dibromoethane	2	0	0	0
C-1,3 - Dichloropropene	2	0	0	0
t-1,3 - Dichloropropene	2	0	0	0
Acrolein	26	0	0	0
1,4-Dichlorobenzene	28	0	0	0
Bromoform	28	0	0	0
1,3 - Dichloropropane	26	0	0	0
1,2 - Dichlorobenzene	29	0	0	0
1,3 - Dichlorobenzene	29	0	0	0
Dibromochloromethane	28	0	0	0
Bromomethane	28	0	0	0
References 3				

Gas recovery systems not only generate condensate in the collection system, but also in gas energy and processing plants. The production of condensate could be through natural or artificial cooling of the gas, or through physical processes such as expansion. Coolers are generally not used. At the surface, typical LFG systems include a condensate collection pot which removes a portion of the entrained water from the vapor prior to entering the vacuum pump or blower. A mist eliminator further removes liquid droplets entrained in the gas.

2.6.2 Condensate Quality

The quality of gas condensate is a function of:

- The nature,
- Age and quality of refuse in the landfill,
- the amount of moisture or liquid in the landfill,
- temperature differences,
- landfill size and configuration,
- type of liner and/or cover materials, and
- climatic conditions.

There is no comprehensive data base on the chemical and physical characteristics of LFG condensate. Data that have been published show that the aqueous phase of LFG condensate generally passes the Toxicity Characteristic Leaching Procedure (TCLP) regulatory 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 a municipal landfill are rarely found to have a non-aqueous phase fraction.

An EPA study(3) provided baseline data on condensate characteristics and chemical analyses on each of the aqueous and hydrocarbon phases. Of the 94 organic compounds identified in six LFG condensate samples, 49 were priority pollutant compounds. Eleven of these compounds were found in every sample in either the aqueous or organic phase: benzene, toluene, phenol, ethyl benzene, benzyl alcohol, bis (2-chloroisopropyl) ether, bis (2-ethylhexyl) phthalate, naphthalene, N-nitrosodimethylamine, 2, 4-dimethylphenol, and 4-methylphenol. The EPA study also identified 15 compounds found in the condensate samples which are on the

Toxicity Characteristic (TC) list. These constituents are listed in Table A-3.

Based on the limited condensate data which are available, it is likely that the hydrocarbon or organic phase of the condensate is ignitable, and thus, should be considered hazardous by RCRA standards. Ignitable wastes are those with a flash point below 60^0C (140^0F). Because of the variability in the existing data, each phase of the LFG stream at each site should be tested to determine the potentially hazardous constituents and their effect on the collection and treatment systems.

2.6.3 Mathematical Description of Gas Flow

Darcy*s Law has often been used to describe laminar flow of fluids through porous media, but it has also been applied to the flow of landfill gases toward a production well. Darcy*s Law for radial flow of landfill toward a recovery well may be expressed mathematically, as follows(5):

$$V_r = - k*\frac{dh}{dl} \tag{2-5}$$

where,

1 = radial distance from the recovery well, m
V_r = apparent gas velocity at distance 1, in/sec
k = permeability coefficient, m/sec
h = hydraulic head, m

$$\text{with } h = \frac{p}{(} + z \tag{2-6}$$

where,

p = total pressure at distance 1, N/m^2
(= specific weight of the gas, kg/m^3 or N/m^3
z = elevation above some arbitrary datum, m

The derivative, dh/dl, represents the hydraulic gradient at distance 1. The negative sign indicates that flow is of decreasing hydraulic head toward the recovery well (8).

The pressure/pressure head, p, can have different units as follows:

TABLE A-3
Toxicity Characteristic Ust Compounds Found In LFG Condensate

Compound	Presence		Regulatory Level[1] (mg/l)	Regulatory Level Exceeded	
	Aqueous	Organic		Aqueous	Organic
Volatile Organic Compounds					
Benzene	X	X	0.5	X	X
2-Butanone (MEK)	X		200.0	X	
Carbon tetrachloride	X		0.5	X	
Chlorobenzene	X[2]	X	100.0		X
Chloroform	X[2]	X	6.0		X
1,2-Dichloroethane			0.5		
1,1-Dichloroethene			0.7		
Tetrachloroethylene	X	X	0.7	X	X
Trichloroethylene	X	X	0.5		X
Vinyl chloride			0.2		
Acid and Base/Neutral Compounds					
Cresols, Total			200		
1,4-Dichlorobenzene	X	X	7.5		X
2,4-Dinitrotoluene			0.13[3]		
Hexachlorobenzene			0.13[3]		
Hexachlorobutadiene			0.5		
Hexachloroethane			3.0		
Nitrobenzene	X		2.0		
Pentachlorophenol			100.0		
Pyridine			5.0[3]		
2,4,5-Trichlorophenol			400.0		
2,4,6-Trichlorophenol			2.0		

[1] Regulatory Level according to the TC List in 40 CFR 261.24 (Table 1)
[2] Detected at levels too low to quantify
[3] Quantitation limit is greater than the calculated regulatory level. The quantitation limit therefore becomes the regulatory limit.

1 bar = 10^5 N.m^{-2}
= 0.987 atmospheres
= 14.5 psi
= 10^6 dynes.cm^{-2}
= 100 KPa
= 1020 cm column of water
= 75.01 cm column of mercury (Hg)

Darcy*s Law applies only to laminar flow; that is, the resistive forces of viscosity predominate. Reynold*s number is usually used to verify the laminar flow. Reynold*s number is defined by the following equation:

$$Re = p*\frac{v*D}{\mu} \qquad (2\text{-}7)$$

where,
Re = Reynold*s number, dimensionless
μ = absolute viscosity of the fluid, Pa.sec.m^{-2}
D = density of the fluid, kg.m^{-3}
v = velocity of flow, m.sec^{-1}*
D = mean grain diameter of the porous medium, m

Previous works found that laminar flow occurs when the Reynold*s number is in the range of 1 to 10. This means that Darcy* law applies only to very slowly moving water/gas. Maximum velocity, v, at the refuse/recovery well interface was found to be in order of 0.3 cm/sec(7).

Other references assume laminar flow conditions if the change in pressure ()P) is less than 12 inches of water column.

2.7 ESTIMATION OF GAS EMISSION

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. The current approach to modeling the gas generation is to employ a simplified model, consistent with fundamental principles. Several models are available for estimating the LFG generation rate using site-specific input parameters. Three relatively simplistic models are the Palos Verdes, Sheldon

Arleta and Scholl Canyon models. The Palos Verdes and Sheldon Arleta will not be discussed in this ETL. Details on these models can be found elsewhere[5]. There are other models such as the Theoretical model and the GTLEACH-I model. The GTLEACH-I treats the landfill as a fixed-film microbial treatment process operating in batch-wise configuration with a continuous dilution and wash out. However, the GTLEACH-I model requires extensive input data which include numerous initial concentrations, moisture content, and leachate flow rate (4). Due to complicated input data requirements, the GTLEACH-I model will not be discussed in this ETL.

2.7.1 Scholl Canyon Model

The Scholl Canyon Model is a model which assumes that CH_4 generation is a function of first-order kinetics. This model ignores the first two stages of bacterial activity and is simply based on the observed characteristics of substrate-limited bacterial growth. The parameters of this model are empirically determined by fitting the empirical data to the model to account for variations in the refuse moisture content and other landfill conditions. The gas production rate is assumed to be at its peak upon initial placement after a negligible lag time during which anaerobic conditions are established and decreases exponentially (first-order decay) as the organic content of the waste is consumed. Average annual placement rates are used, and the time measurements are in years. The model equation takes the form:

$$Q_{CH4} = L_0 * R\,(e^{-kc} - e^{-kt}) \tag{2-8}$$

Where:

Q_{CH4} = CH4 generation rate at time t, m^3/yr

L_0 = potential CH_4 generation capacity of the waste, m^3/Mg

R = average annual acceptance rate of waste, Mg/yr

k = CH_4 generation rate constant, 1/yr

c = time since landfill closure, yr (c=0 for active landfill)

t = time since initial waste placement, yr.

The model could be further refined by dividing the landfill into smaller submasses to account for the landfill age over time. If a constant annual acceptance rate (R) is assumed, the CH_4 generated from the entire landfill (sum of each submass contribution) is maximum at the time of landfill closure. Lag time due to the establishment of anaerobic conditions could also be incorporated into the model by replacing “c” with “c + lag time” and “t” by “t + lag time”. The lag time before which anaerobic conditions are established may range from 200 days to several years(11).

The refined Scholl Canyon Model equation then takes the following form:

$$Q = 2 * k * L_0 * R \left(e^{-k(t - lag)}\right) \qquad (2\text{-}9)$$

Where:
Q = LFG generation rate at time t, m^3/yr
L_0 = potential CH_4 generation capacity of the waste, m^3/Mg
R = average annual acceptance rate of waste, Mg/yr
k = CH_4 generation rate constant, 1/yr
t = time since initial waste placement, yrs.
lag = time to reach anaerobic conditions, yrs.

2.7.2 Theoretical Models

The theoretical CH_4 generation capacity (L_0) can be determined by a stoichiometric method(11) which is based on a gross empirical formula representing the chemical composition of the waste. If a waste contains carbon, hydrogen, O_2, nitrogen and sulfur (represented by $C_aH_bO_cN_dS_e$), its decomposition to gas is shown as:

$$C_aH_bO_cN_dS_e \;\mathbf{--->}\; vCH_4 + wCO_2 + xN_2 + yNH_3 + zH_2S + \text{humus} \qquad (2\text{-}10)$$

The composition of LFG, during anaerobic conditions, is approximately 50 percent CH_4, 40 to 50 percent $C0_2$ and 1 to 10 percent other gases.

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 for the refuse (or specific waste components) is approximated by performing overall 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(11) to range from approximately 6 to 270 m^3 CH_4 per metric ton of waste for municipal landfills.

The CH_4 generation rate constant, k, estimates how rapidly the CH_4 production rate falls after the waste has been placed (since the method assumes the rate is at its maximum upon placement). The value of k is strongly influenced by:

- temperature,
- moisture content,
- availability of nutrients, and
- pH.

CH_4 generation increases as the moisture content increases up to a level of 60 to 80%, at which the generation rate does not increase(7). Values of k obtained from literature, laboratory simulator results, and back-calculated from measured gas generation rates range from 0.003/yr to 0.21/yr(11).

Once these constants have been estimated, the rate of waste placement and the time in the landfill life cycle determine the estimated gas emission rate.

2.7.3 Regression Model

The actual data from 21 U.S. landfills were used to develop a statistical model to estimate the CH_4 gas generation rate(13). Based on the preliminary data analysis, a linear model appeared to be sufficient to model CH_4 generation rate. Selection of the variables for the regression model was based on the results of the correlation and scatter plots. For most of the models that use single landfill parameter, the intercept was insignificant. Hence, the simple model was found to be a no-intercept regression model correlating CH_4 recovery rate to the refuse mass according to:

$$Q_{CH4} = 4.52\ W \tag{2-11}$$

where,

Q_{CH4} = CH_4 flow rate (m3/min)
W = mass of refuse (metric tons)

The regression coefficient (R^2) for this correlation was 0.50. No other variable except the mass of refuse and the depth of the landfill was found to have any effect on the CH_4 production rate. No functional model was found linking CH_4 production to climate variables. The upper and lower 95% confidence limits for the slope in the above equation are 6.52 and 2.52 m3 CH_4 per ton of refuse.

2.7.4 Comparison of the Scholl Canyon and Regression Models

The characteristics of Scholl Canyon Model are:

- It is a theoretical model based on a first-order decay equation;
- It has two adjustable variables; namely L_0, and k which should be developed for each landfill;
- When the variables are known, the model could be dependable;
- The model is impractical for use on a global scale where site-specific data are not available.

The regression model has the following characteristics:

- It is a simple empirical model based on actual performance data from 21 landfills.

- It requires only one variable (i.e., quantity of refuse in the landfill) to estimate the OH_4 emission rate.

- Additional observations could be easily added to the model to further refine the model.

- The model may over-estimate the emission rate for wastes with low cellulose content, and

- The model is found satisfactory in estimating CH_4 production rate on a global basis.

The two models were compared with each other in predicting the emission rate from the 21 U.S. landfills. The comparison was made by calculating the ratio of model-predicted to actual emission rates, the mean and standard deviations of the ratios from both the regression model and the Scholl Canyon Model are then obtained. The closer this ratio is to unity, the more successful the model is in estimating the emission rate. Table A-4 shows the comparison of the two models. The Scholl Canyon Model was run with three different values for the potential CH_4 generation capacity (L_0). The Scholl Canyon Model seems to underpredict the emission in Run 1 where L_0 was 50 m^3/ton. In Run 2, where L_0 is set to 162 m^3/ton, the model is very accurate and the mean ratio is 1.07. In Run 3, L_0 is assumed at 298 m^3/ton, and the model overestimates the CH_4 emission rates. The regression model predicts the emission rate which falls between the Scholl Canyon Model in Runs 1 and 3. It is important to note that the regression study uses CH_4 recovery rate as a surrogate for OH_4 emissions. The validity of this substitution is unknown, therefore the emissions could be both overestimated and underestimated.

Despite these concerns, the regression model is very simple and easily adapted to global emissions estimation.

Table A-4

Comparison of Performance of Scholl Canyon and Regression Model

	Scholl Canyon Model			Regression Model
	Run 1	Run 2	Run 3	
Site Number	Pred/Actual	Pred/Actual	Pred/Actual	Pred/Actual
1	0.16	0.40	0.73	0.52
2	0.48	1.21	2.23	1.55
3	0.28	0.71	1.31	0.83
4	0.22	0.55	1.01	0.62
5	0.58	1.44	2.66	1.95
6	0.24	0.60	1.10	0.73
7	0.46	1.16	2.14	1.50
8	0.37	0.93	1.71	1.15
9	0.36	0.90	1.67	1.15
10	0.25	0.64	1.17	0.83
11	0.23	0.57	1.05	0.85
12	0.54	1.34	2.47	1.72
13	0.16	0.39	0.72	0.57
16	0.33	0.82	1.52	1.02
17	0.49	1.23	2.26	1.73
20	0.41	1.02	1.88	1.24
21	0.15	0.36	0.67	0.47
22	0.19	0.47	0.87	0.57
23	1.74	4.35	8.00	6.32
24	0.54	1.34	2.46	1.6
25	0.82	2.06	3.79	2.34
Mean	0.43	1.07	1.97	1.39
Std. Deviation	0.34	0.85	1.56	1.24

3.0 LANDFILL OFF-GAS CONTROL APPLICABILITY

This section describes the current technologies utilized for LFG emission control. The control techniques include LFG gas collection and disposal, LFG treatment for energy recovery, and condensate management. LFG control technologies are continually improving; however, the technologies described in this ETL are well established and can be found in industrial applications.

3.1 LFG COLLECTION

There are two gas collection strategies:- passive and active. A passive system functions on the principle that natural pressure gradient and convection mechanisms which move the LFG. Passive systems provide corridors to intercept lateral gas migration and channel the gas to a collection point or a vent. These systems use barriers to prevent migration past the interceptors and the perimeter of the landfill. Active systems move the LFG under induced negative pressure (vacuum). The zone of negative pressure created by the applied vacuum induces a pressure gradient towards a collection point which is either a well or horizontal collector pipe.

Detailed discussions of LFG collection system design can be found in Chapter 4, Design Considerations.

3.1.1 Comparison of Various Gas Collection Systems

The efficiency of a passive collection system depends on good containment of the LFG to prevent direct emission to the ambient air. Generally, passive collection systems have lower collection efficiencies than active systems, since they rely on natural pressure or concentration gradients to drive gas flow rather than a stronger, mechanically-induced pressure gradient. A well—designed passive system, however, can be nearly equivalent in collection efficiency to an active system if the landfill design includes synthetic liners in the landfill liner and cover.

Since a passive systems rely on venting, in the event that the vent is blocked by moisture or frost, the gas seeks other escape routes including moving into surrounding formations.

Passive systems are not considered reliable enough to provide an exclusive means of protection. With their concentrated vent gas, passive systems may be considered as an uncontrolled air emissions point source by regulatory agencies.

In addition, passive venting systems raise the potential for nuisance odor problems because there is no positive system for odor management.

The construction of passive systems is less critical than active systems, because the collection well is under positive pressure and air infiltration from the surface is not as great a concern. Additionally, elaborate well head assemblies are not required for passive systems since monitoring and adjustment are not usually necessary in these systems.

Active systems are usually utilized where a higher degree of system reliability is required than can be accomplished with a passive collection system. Based on theoretical evaluations, a well-designed active collection system is considered the most effective means of gas collection(3). Table A-5 presents a comparison of various gas collection systems.

3.2 LFG CONTROL TECHNOLOGIES

LFG can be either combusted with no energy recovery; combusted with energy recovery or purified for introduction to an off-site co-generation facility or release to atmosphere without treatment.

The non-energy recovery techniques use flares and thermal incinerators. The energy recovery techniques include gas turbines, internal combustion engines, and boiler-to-steam turbine systems, all of which generate electricity from the combustion of LFG. Boilers may also be used at the landfill site or off-site to recover energy from LFG in the form of steam.

TABLE A-5 COMPARISON OF VARIOUS COLLECTION SYSTEMS

Collection system type	Preferred applications	Advantages	Disadvantages
Active vertical well collection systems	Landfills employing cell-by-cell landfilling methods Landfills with natural depressions such as canyon	Cheaper or equivalent in costs when compared to horizontal trench systems	Difficult to install and operate on the active face of the landfill (may have to replace wells destroyed by heavy operative equipment.
Horizontal trench collection systems	Landfills employing layer-by-layer landfilling methods	Easy to install since drilling is not required	The bottom trench layer has higher tendency to collapse and difficult to repair once it collapses Has tendency to flood easily if water table is high Difficult to maintain uniform vacuum along the length (or width) of the landfill. Must be installed while the landfill is being constructed; not applicable for constructed landfills.
Passive collection systems	Landfills with good containment (side liners and cap)	Cheaper to install and maintain if only a few wells are required Lower in operation & maintenance cost	

Source: 3

3.2.1 Non-Energy Recovery

3.2.1.1 Flare

Flares are used at landfills as the main method of air emission control and as a back-up to an energy recovery system. Flaring is an open combustion process in which the 0_2 required for combustion is provided by either ambient air or forced air. LFG is conveyed to the flare through the collection header and transfer lines by one or more blowers. A knock-out drum is normally used to remove gas condensate. The LFG is usually passed through a water seal before going to the flare. This prevents possible flame flashbacks which occur when the gas flow rate to the flare is too low and the flame front moves down into the stack.

Two types of flare systems are generally available: open-flame flare and enclosed flare. Each flare type has advantages and disadvantages. Both types of flares have been used for LFG treatment.

Oven-Flame Flare. An open-flame flare or candle flare represents the first generation of flares. The open-flame flare was mainly used for safe disposal of combustible gas when emission control had not been a requirement. Open-flame flares have also been widely used in LFG combustion. Open-flame flare design and the conditions necessary to achieve 98 percent reduction of total hydrocarbon are described in 40 CFR 60.18.

The advantages of open-flame flares are:

- simple design since combustion control is not possible,
- ease of construction,
- most cost-effective way of safely disposing of landfill gases, and
- open-flame flares can be located at ground level or elevated.

The major disadvantage of all open-flame flares are:

- do not have the flexibility to allow temperature control, air control, or sampling of combustion products due to its basic design,

- not possible to design a closed-loop system to accurately measuring flow rates or emissions from an open-flame flare for the following reasons: 1) Sample probes placed too close to the flame will measure high $C0_2$ and hydrocarbon levels; 2) Samples taken further away from the flame are diluted unpredictably by air.

- if emissions sampling and testing are required, an enclosed type flare will be needed.

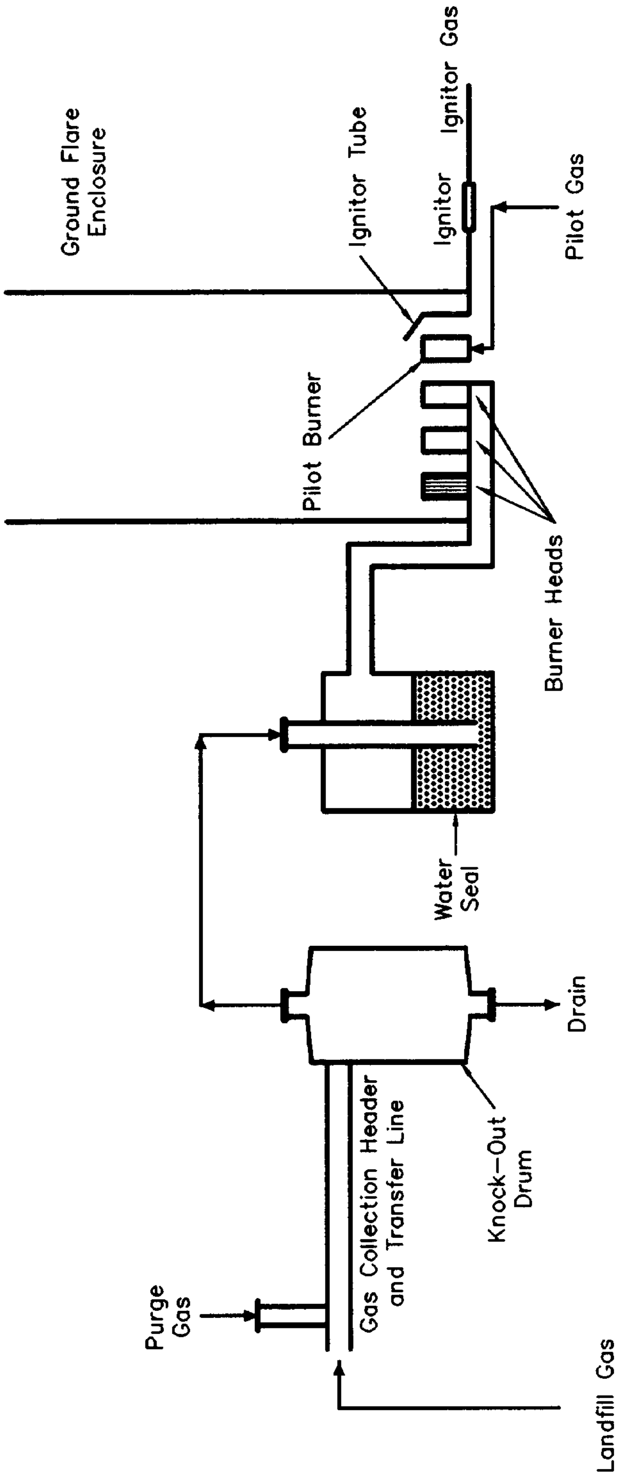
Enclosed Flares. Enclosed flares differ from open flares in that both LFG and air flows are controlled. While LFG is pushed through the flame arrestor and burner tips by a blower, the flare stack pulls or drafts the air through air dampers and around burner tips. The stack acts as a chimney, so its height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

- They provide a simple means of hiding all or parts of the flame (i.e., neighbor friendly), and

- emission monitoring may be mandatory.

A typical enclosed flare system is shown in Figure A-4.

Depending on air regulations in each state, enclosed flares with an automatic air damper control may be required. Periodic sampling of these flares is conducted to ensure that an emission reduction of 98 percent is being achieved.



ENCLOSED FLARE SYSTEM

FIGURE A–4
(SOURCE 2)

3.2.1.2 Thermal Incineration

Thermal incineration processes use the basic operating principle of a thermal incinerator: any organic chemical heated to a high enough temperature in the presence of sufficient O_2 will be oxidized to CO_2 and water. The theoretical temperature required for thermal oxidation to occur depends on the structure of the chemical involved. Some chemicals are oxidized at temperatures much lower than others. Where thermal incinerators are used to control vent streams from LFG recovery systems, auxiliary fuel is typically required.

Thermal incinerators are applicable as a control device for any vent stream containing NMOCs. In the case of LFG emission, however, their use is primarily limited to control of vent streams from CH_4 recovery systems.

3.2.2 Energy Recovery Systems

In large municipal landfills, LFG is being developed as an energy resource. Military landfills, due to its size and waste types, usually do not generate methane gas in large quantity to be economically recovered. LFG in military landfills is therefore contained rather than recovered for energy use. Energy recovery options, however, are briefly discussed for the reader information.

The following four approaches have been adopted for recovering energy from LFG:

- Use of LFG to fuel gas turbine;
- Generation of electricity by the operation of an internal combustion engine with LFG;
- Use of LFG directly as a boiler fuel; and
- Upgrading the gas quality to pipeline quality for delivery to utility distribution systems.

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 (6,900 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. 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.

3.2.2.1 Gas Turbines

Process Description. Gas turbines aspire ambient air, compress it and combine it with fuel in the combustor. The combustor exhaust stream flows to the power turbine which burns the fuel to heat it, then expands it in the power turbine to develop shaft horsepower. This shaft power drives the inlet compressor and an electrical generator (or some other load).

Two basic types of gas turbines have been used in landfill applications: simple cycle and regenerative cycle. The gas temperatures from the power turbine range from 430 to 600^{0}C (800 to l,100^{0}F). The regenerative cycle gas turbine is essentially a simple cycle gas turbine with an added heat exchanger. Thermal energy is recovered from the hot exhaust gases and used to preheat the compressed air. Since less fuel is required to heat the compressed air to the turbine inlet temperature, the regenerative cycle improves the overall efficiency of the gas turbine(3).

Based on field tests and information provided by manufacturers, these turbines are capable of achieving greater than 98 percent destruction of NMOC.

Applicability. The applicability of gas turbines depends on the quantity of LFG generated, the availability of customers, the price of electricity, and environmental issues. There are about 20 landfills in the U.S. which employ gas-fired turbine(3).

Advantages of using gas turbines are:

- Gas turbines have lower emissions of NOx, CO and PM than comparatively sized of combustion engines;

- Gas turbines are less sensitive to fluctuations in influent Btu gas than are internal combustion engines;
- Using a dual oil and oil filter system, shutdowns for minor maintenance are less frequent;
- No gas condensate is formed in the process;
- Gas turbines are more mechanically reliable since they have fewer moving parts, no reciprocating moving parts, no valves, cams, belts, radiators, water cooling and ignition system (other than for starting); and
- Because there is no lube oil in the exhaust, air emissions are less than with internal combustion engines. Excess combustion air and high temperatures accomplish complete combustion of carbon monoxide and residual hydrocarbons.

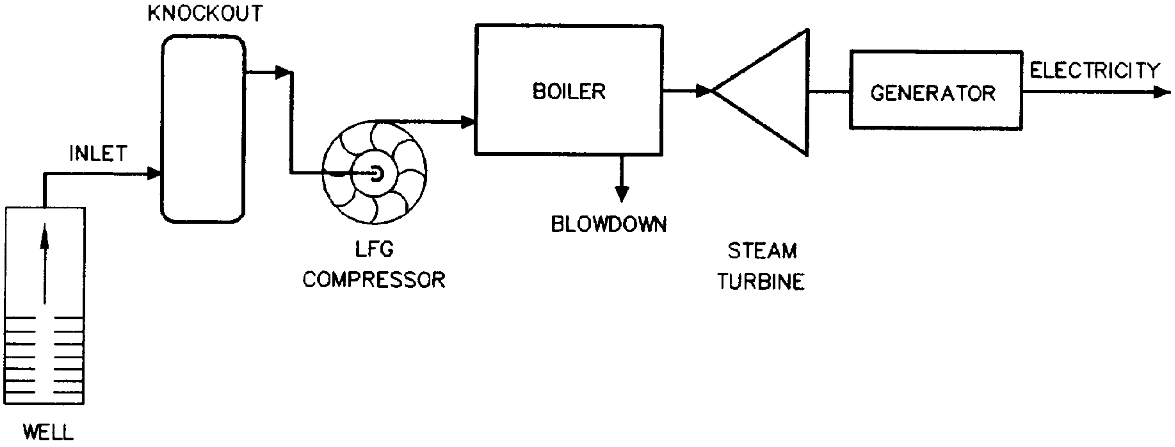
Disadvantages of using gas turbine engines are:

- O&M costs increase dramatically if the engine is used only intermittently (i.e., for peak power use);
- Turbine blades are sensitive to foreign particles in the gas and air streams;
- Oil deposits on blades can cause units to become unbalanced; and
- They require inlet compression of the fuel feed and air between 160 and 200 psig, thus ancillary compressor equipment is required.

A schematic of an LFG to steam generation plant is presented in Figure A-5.

3.2.2.2 Internal Combustion (I.C.) Engines

Process Description. Reciprocating internal combustion engines produce shaft power by confining a combustible mixture



SCHEMATIC OF LFG TO TURBINE ELECTRIC GENERATION

FIGURE A-5

(SOURCE 2)

in a small volume between the head of a piston and its surrounding cylinder, causing this mixture to burn, and allowing the resulting high pressure products of combustion gas to push the piston. Power is converted from linear to rotary form by means of a crankshaft(3).

The major problem with use of combustion engines for these applications is selection of the fuel gas compressor. Matching the gas compressor to the available gas and engine requirements is one of the major difficulties in the design of the completed gas-to-energy project. Many projects select the gas compressor by trial and error.

Applicability. I.C. engines are being used for landfill off-gas control because of their short construction time, ease of installation, and operating capability over a wide range of speeds and loads. I.C. engines fueled by LFG are available in capacities ranging from approximately 500 KW up to well over 3,000 KW.

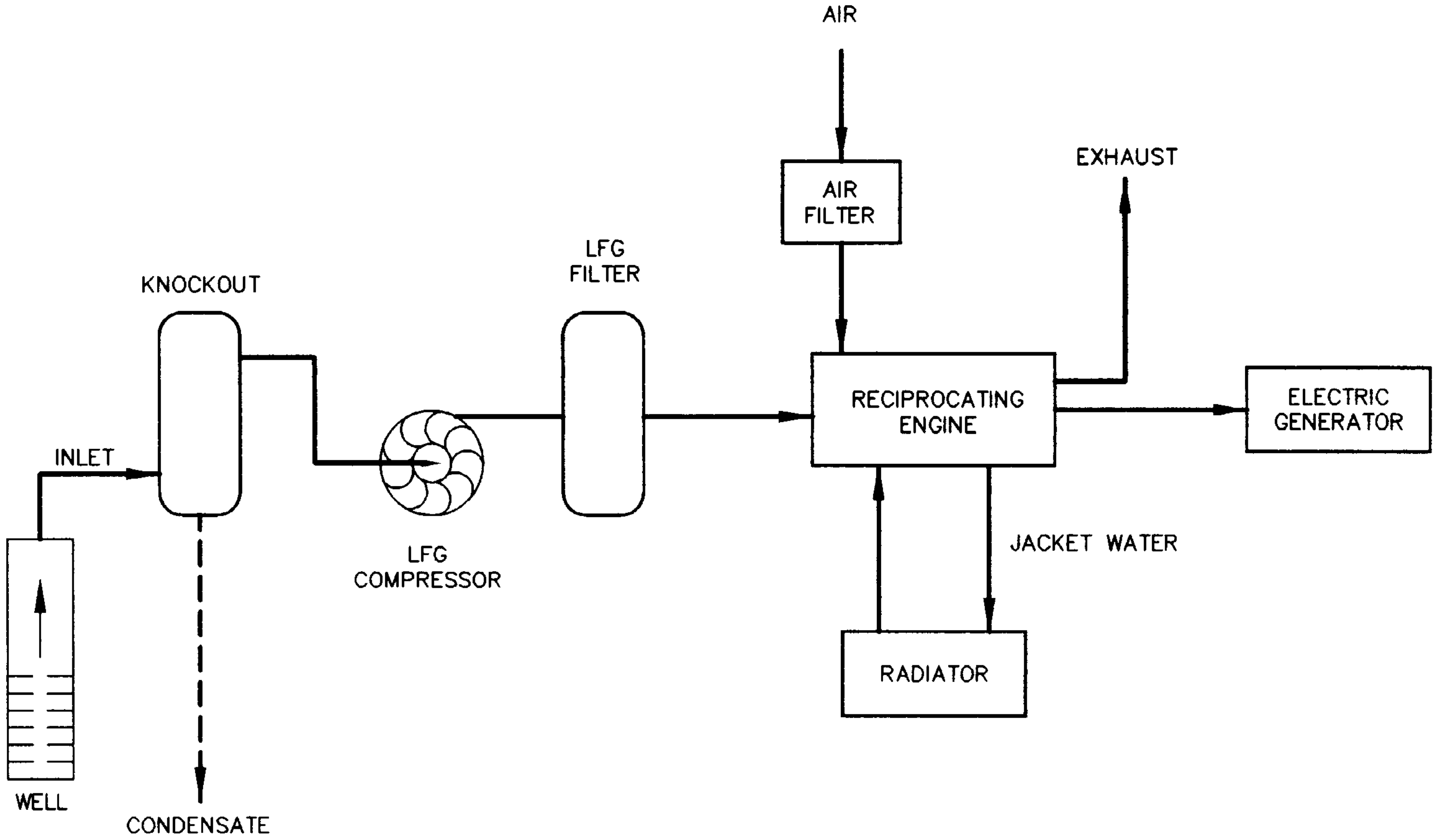
Advantages of using I.C. engines are:

- short construction time;
- can achieve 98 percent reduction of NMOC;
- NO_x emissions from these engines are lower than comparable natural gas fired engines;
- commonly used technology;
- wide range of availability; and
- efficient at full load and partial load.

Disadvantages of using I.C. engines are:

- the fuel gas compressor to match the I.C. engines;

A schematic of an LFG I.C. generation plant is presented in Figure A-6.



SCHEMATIC OF LFG TO INTERNAL COMBUSTION
FOR ELECTRICAL GENERATION
FIGURE A-6
(SOURCE 2)

3.2.2.3 Boiler or Steam Generator

Process Description. The majority of industrial boilers are of water tube design. In a water tube boiler, hot combustion gases contact the outside of heat transfer tubes which contain hot water and steam. These tubes are interconnected by a set of drums that collect and store the heated water and steam. The water tubes are of relatively small diameter, 5 cm (2 inches), providing rapid heat transfer, rapid response to steam demands, and relatively high thermal efficiency. Energy transfer efficiency can be above 85 percent. Additional energy can be recovered from the flue gas by preheating combustion air in an air preheater or by preheating incoming boiler feed water in an economizer unit(3).

The majority of LFG-fired boilers are industrial boilers with corresponding heat inputs of approximately 10.5 x 10^6 Btu/hr (350 scfm at 50 percent CH_4) to 90 x 10^6 Btu/hr (3,000 scfm at 50percent CH_4). The most recent power generation technology to utilize LFG is the steam generator using the Rankine Cycle. The LFG is burned in a boiler to produce superheated steam. The steam drives a steam turbine generator for power production. The benefit of Rankine Cycle power production from the combustion of LFG is the low heat rate of 10,000 Btu/KW. This is the lowest rate and highest efficiency of all of the LFG-fired power generation systems to date. In addition, the Rankine Cycle has been demonstrated to be one of the lowest emitters of NO_x and ROG of any LFG-fired equipment.

Applicability. LFG-fired boilers may be utilized in two ways. The LFG may be routed to an on-site boiler or piped and sold to an off-site boiler to supply heat or hot water. The LFG may also be routed to an on-site boiler to generate steam to produce electricity.

Advantages of using LFG-fired boilers are:

- low NO_x emissions,
- small physical size, and

- low O&M cost.

Disadvantages of using LFG-fired boilers are:

- high initial capital investment,
- high fuel pressure required,
- inefficient at partial load, and
- large amount of condensate in the process.

3.2.2.4 LFG Purification Techniques

The LFG has a typical composition of 40 to 60 percent CH_4, 40 to 50 percent $C0_2$, 1 to 2 percent of air and inert gases and other impurities such as halogenated hydrocarbons, volatile solvents, organic sulfur compounds and H_2S. It is critical to almost all LFG end-usages that the CH_4 products be clean and not contain the impurities.

Purification techniques to upgrade the LFG to a high Btu value may include the followings:

- removal of impurities,
- removal of $C0_2$,
- removal of water, and
- gas compression to pipeline pressure.

Impurities removal techniques may include the use of adsorption, absorption or membranes to process raw LFG to pipeline quality natural gas. All purification techniques involve removal of water before removing $C0_2$. The water is removed by either absorption with glycol or adsorption with silica gel, alumina, or molecular sieves. The NMOC removal method depends on the different $C0_2$ removal techniques chosen and the composition of the LFG. Usually the same techniques used for $C0_2$ removal are also used to remove NMOC by simply adding an extra adsorption, absorption, or condensation step.

In general, the selection of a recovery technique depends on the gas generation rate, the location of the plant, the availability of a market for the recovered energy, and the environmental impacts.

4.0 LFG DESIGN CONSIDERATIONS

4.1 GENERAL

This chapter discusses parameters the designer should consider for the design of LFG control systems.

The design process for LFG control typically consists of two phases. Phase 1 is an investigation to determine the technical and economical viability of the LFG recovery system. Phase 2 is the design of the full-scale system.

4.2 PHASE 1: INVESTIGATION

The investigation phase typically consists of the following steps:

- collect and review existing data,
- conduct interviews and site inspection,
- review data base information,
- conduct a screening process, and
- conduct a field tests.

4.2.1 Data Collection

Existing site data can be obtained from available records on the site, and from regulatory, and other government agencies. These include permit documents, regulatory correspondence, waste receipt volumes, waste type, gas data, leachate data and ground-water data, closure date, etc. Information on the site will permit the designer to established a data base for completing design calculations. It will also allow the designer to determine whether additional data gathering activities are necessary.

4.2.2 Interview and Site Inspection

Interviews should extend to all concerned parties familiar with landfill operations including landfill owner, operator and appropriate officials. This information will provide the designer with the current status of the site, any current environmental problems or ones that could develop in the future.

Inspection of the site and its surroundings will aid the designer in verifying the data collected and at the same time configuring the conceptual design of the LFG collection and recovery system.

4.2.3 Review of Data Base Information

A review of data base information on existing facilities of the same type will provide the designer with up-dated technologies, their effectiveness and costs.

4.2.4 Conduct Screening

The preliminary design screening process should consider:

- recovery technique,
- regulatory requirements for collection and treatment,
- comparative cost, and
- advantages and disadvantages of each technique.

4.2.5 Field Tests

To implement LFG collection/treatment options, certain data are required to properly design a system and to select the appropriate gas recovery and control system. The data required include chemical characteristics of the gas and the gas-generation rate. For existing landfills, data can be collected as described in the following paragraphs. For new landfills, assumptions must be made on the chemical and physical characteristics of the gas based on historical data from similar installations.

4.2.5.1 Characterization of Gaseous Emissions

LFG composition is one of the determinations that is of principal interest in any evaluation of potential gas treatment methods. Some methods to collect LFG samples are: barhole probe, permanent gas monitoring probes, and gas extraction wells.

EPA has developed three test methods for proposal of air emission control regulations. These include Method 2E - Determination of Landfill Gas Production Flow Rate, Method 3C - Determination of Carbon Dioxide, Methane, Nitrogen, and oxygen from Stationary Sources, and Method 25C - Determination of NMOC in landfill Gas. Detailed of these methods are described in the EPA document EPA-450/3-90-011a, Air Emissions from Municipal Solid Waste Landfills- Background Information for Proposed Standards and Guidelines. The following paragraphs briefly describe these methods.

4.2.5.2 Determination of Gas Generation Rate: EPA Method 2E

EPA Method 2E measures LFG production flow rate from MSW landfills and is used to calculate the flow rate of NMOC compounds from landfills. Extraction wells are installed in a cluster of three or five dispersed locations in the landfill and a blower extracts the LFG from the wells. LFG composition, landfill pressure and orifice pressure differentials are measured and the LFG production flow rate is calculated.

4.2.5.3 Determination of Non Methane Organic Compounds: EPA Method 3C

EPA Method 3C applied to the analysis of carbon dioxide ($C0_2$), methane (CH_4), nitrogen (N_2), and oxygen (0_2) in samples from MSW landfills and other sources when specified in an applicable Subpart of the regulation.

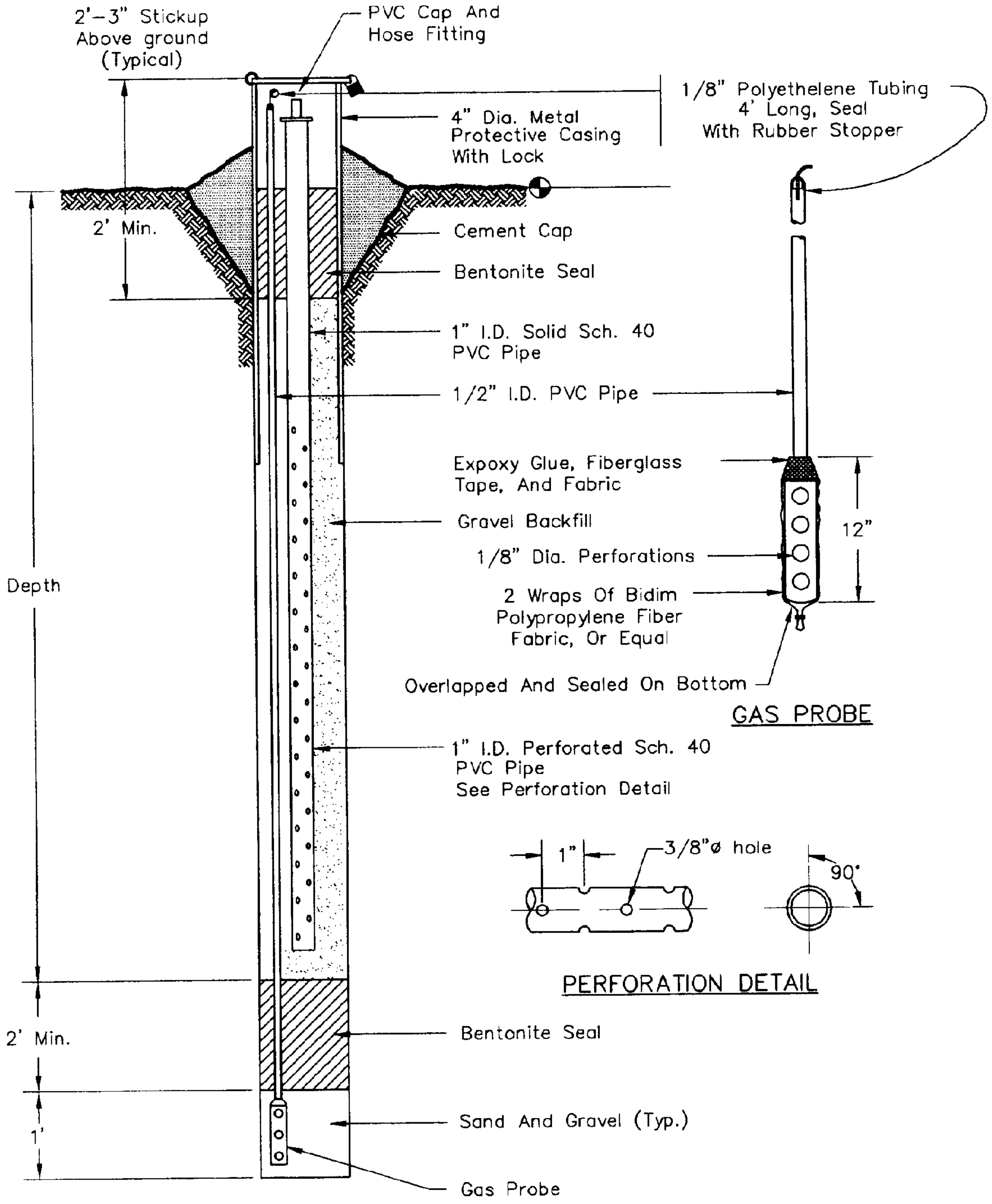
A portion of the sample is injected into a gas chromatograph (GC) and the $C0_2$, CH_4, N_2, and O_2 concentrations are determined by using a thermal conductivity detector (TCD) and integrator.

4.2.5.4 Determination of Non Methane Organic Carbon: EPA Method 25C

EPA Method 25C is applicable to the determination of NMOC (as carbon) in LFGs. A perforated sample probe is driven below the bottom of the landfill cover. A sample of the LFG is extracted with an evacuated cylinder. A portion of gas is injected into a gas chromatographic (GC) column to separate the NMOC from CO, $C0_2$ and CH_4. The NMOCs are oxidized to $C0_2$, and quantified with a flame ionization detector (FID). While this procedure is complex, it eliminates the variable response of the FID associated with different types of organic compounds. A typical gas probe monitoring detail is presented in Figure A-7.

4.2.5.5 Pilot-Scale Field Testing

Gas-phase permeability tests are the most common type of pilot-scale tests performed. These are generally used during the initial design stage of a gas recovery system. Gas-phase permeability tests provide the following design information:



TYPICAL GAS PROBE MONITORING DETAIL

FIGURE A-7

N.T.S.

(SOURCE 14)

- a measure of the pressure distribution associated with an applied vacuum,

- gas flow rates,

- contaminant concentrations and recovery rates,

- gas-phase permeabilities at the site, and

- moisture removal rates.

The gas-phase permeability tests (also called pneumatic pump tests) offer an alternative to indirect and laboratory methods for calculating air permeability. These tests tend to provide more realistic estimates of air permeability and are more appropriate for gas recovery testing. Air-phase permeability tests are described in several documents(2,5).

A number of investigators(18,19) have developed transient and steady-state solutions for air flow, which can be used for analysis of pneumatic pump test data.

4.3 PHASE 2: FULL-SCALE DESIGN

The full-scale design should start after selecting an LFG control system that is cost-effective and meets applicable regulations.

The primary design elements of the LFG management system include gas collection and treatment. Presented below are design considerations of these systems.

4.4 LFG COLLECTION

Two types of LFG collection systems are discussed:

- passive collection, and
- active collection.

4.4.1 Passive Collection Systems

Passive collection uses either collection wells or trenches to collect LFG. The efficiency of a passive collection system depends on good containment of the LFG. Collection wells and trenches typically use vent pipes which either discharge the gas to the atmosphere or to treatment.

4.4.1.1 <u>Gas Wells</u>

Passive collection systems rely on natural pressure or concentration gradients in the landfill to move the gas.

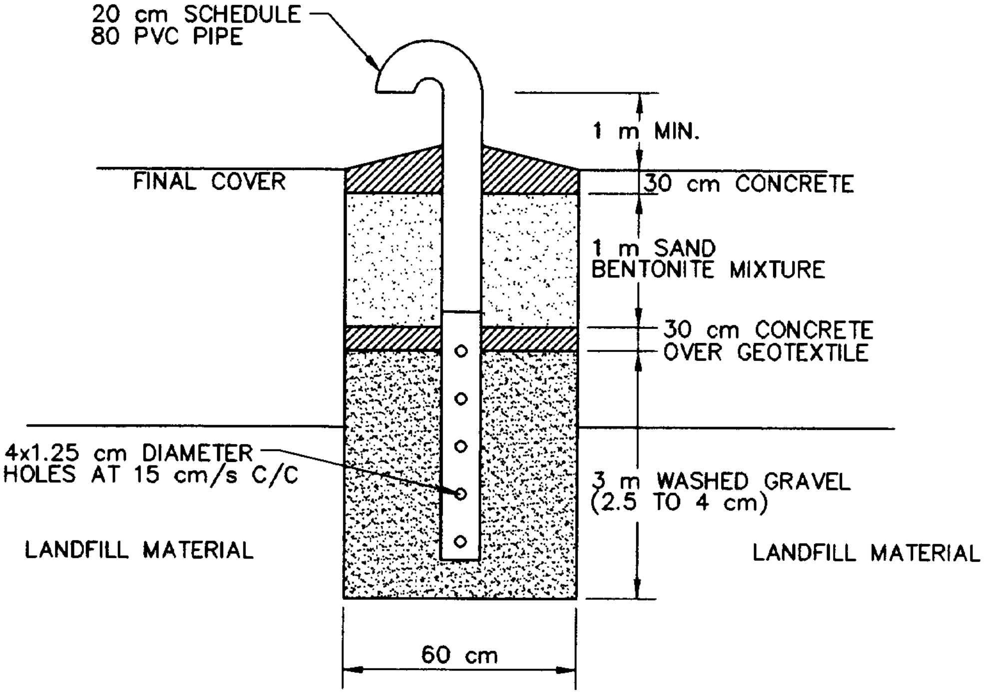
The construction of passive systems is similar to that of active wells which will be discussed in Section 4.4.2. However, the manifold connection shown would not be constructed. Additionally, elaborate well head assemblies are not required since monitoring and adjustment are not usually necessary. A good type of seal is always used to connect the geomembrane to the gas extraction well. The wells can be constructed as filling proceeds. However, if wells are placed in an existing landfill, they must be drilled into the waste.

Passive wells should generally be located about 10 to 15 meters (33 to 50 feet) from the edge of the wastes and typical not more than one well per acre. Additional wells may be needed further within the body of the wastes to intercept their full depth if the site is benched or sloping. A passive well vent is illustrated in Figure A-8.

4.4.1.2 <u>Trench Collection Systems</u>

Gas collection trenches can be used where vertical extraction wells are not practical, such as in areas where the refuse depth is shallow or where the liquid is high. A drawback of trenches is their tendency to draw in air if the seal over each trench is inadequate. Extreme care should be taken in the design of all vent systems to prevent them from being a source of infiltration through the cover.

Major advantages of trench systems include ease of construction and relatively uniform withdrawal influence areas. However, these trenches are susceptible to crushing as subsequent lifts of waste are placed and susceptible to severing and severe damage as a result of differential settlement of the waste pack. When placed below groundwater levels, these trenches are also subject to flooding. When designing trenches which will be installed below the expected high groundwater or



<u>FIGURE A-8</u>

PASSIVE GAS VENTS

(SOURCE 14)

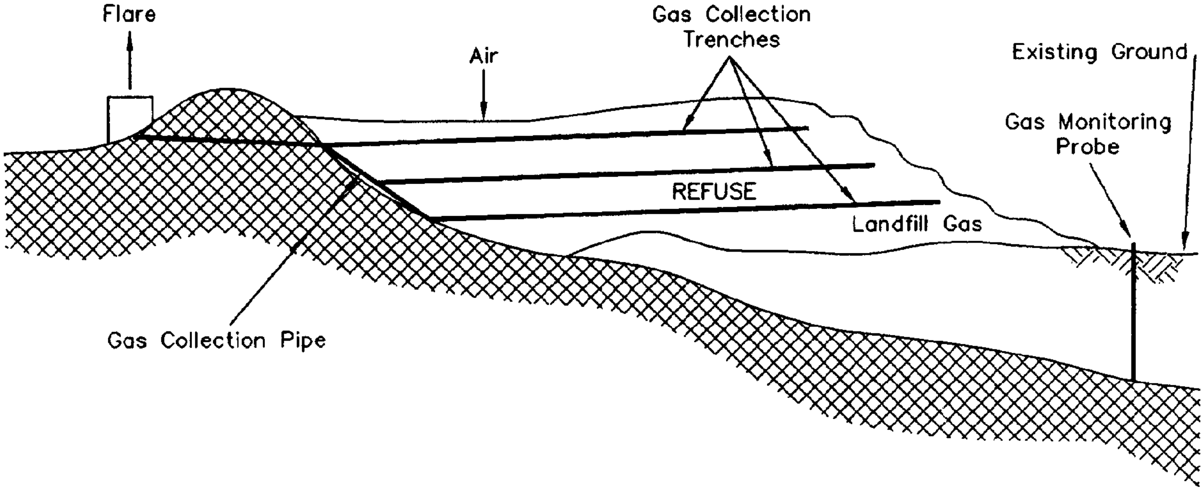
leachate levels, measures should be taken to avoid drawing water into the gas collection system.

The trenches can be vertical or horizontal at or near the base of the landfill. A vertical trench is constructed in much the same manner as a vertical well is constructed. For a new site, horizontal trenches are installed within a landfill cell as each layer of waste is applied. The distance between layers should be no greater than 5m (15 feet). This allows for gas collection as soon as possible after gas generation begins and avoids the need for above-ground piping which can interfere with landfill maintenance equipment. Additional "legs" of the system are connected to the manifold as the landfill grows in areal size or height. Figure A-9 illustrates a horizontal trench collection system.

The horizontal trench pipes may be constructed of perforated polyvinyl chlorides (PVC), high density polyethylene (HDPE), or other suitable strength nonporous material. Due to the corrosive nature of LFG and condensate, corrugated steel is usually not used. The trench should be about 1 meter (3 feet) wide, filled with gravel of uniform size and extend into the refuse about 1.5 m (5 feet) below the landfill cap layer. Trenches should be located between the waste fill and the gas barrier or side of the site.

The side of the trench nearest to the property boundary should be sealed with a low-permeability ($< 10^{-9} m \bullet s^{-1}$) barrier material, such as a synthetic geomembrane to prevent gas migration. The remainder of the trench should be lined with a filter fabric to prevent clogging of the permeable medium.

The gas collection piping enclosed in the trench gravel pack is connected to surface vent pipes of similar construction as the collection piping. Vent pipe spacing should be determined from monitoring and site investigation data, but should generally not be greater than 50 meters apart. Passive vents can be used in combination with horizontal trenches by connecting vents to the pipes with flexible (i.e., settleable) hosing. The flexible hose between the extraction well or trench and the collection header system allows differential movement.



HORIZONTAL TRENCH COLLECTION SYSTEM

FIGURE A-9
(SOURCE 2)

Because of its horizontal layout, the collection header system would be expected to settle more than a vertical extraction well. This flexible connection allows more movement than would be possible if the two pipes were rigidly connected. Sampling ports can be installed allowing monitoring of pressure, gas temperature and concentration, and liquid level.

4.4.2 Active LFG Collection Systems

As described previously, an active collection system consists of a mechanical blower or compressor attached to a system of gas extraction wells or collection trenches. A pressure gradient is created in the wells or trenches, thereby forcing the removal of gas from the landfill. The gas is then piped to a flare, cogeneration unit or other treatment system.

The effectiveness of an active LFG collection system depends greatly on the design and operation of the system. An effective collection system should be designed and configured so as to:

- handle the maximum LFG generation rate,
- effectively collect LFG from all areas of the landfill, and
- provide the capability to monitor and adjust the operation of individual extraction wells and trenches.

Air intrusion is a major concern in the design of the active LFG collection system. Air intrusion may naturally permeate through the landfill cover and into the refuse. Natural permeation is particularly severe in arid regions where dry cover soils are easily penetrated by air.

An active collection system has four major components:

- gas extraction wells (or horizontal trenches),
- gas moving equipment,
- LFG treatment units, and
- condensate removal and disposal units.

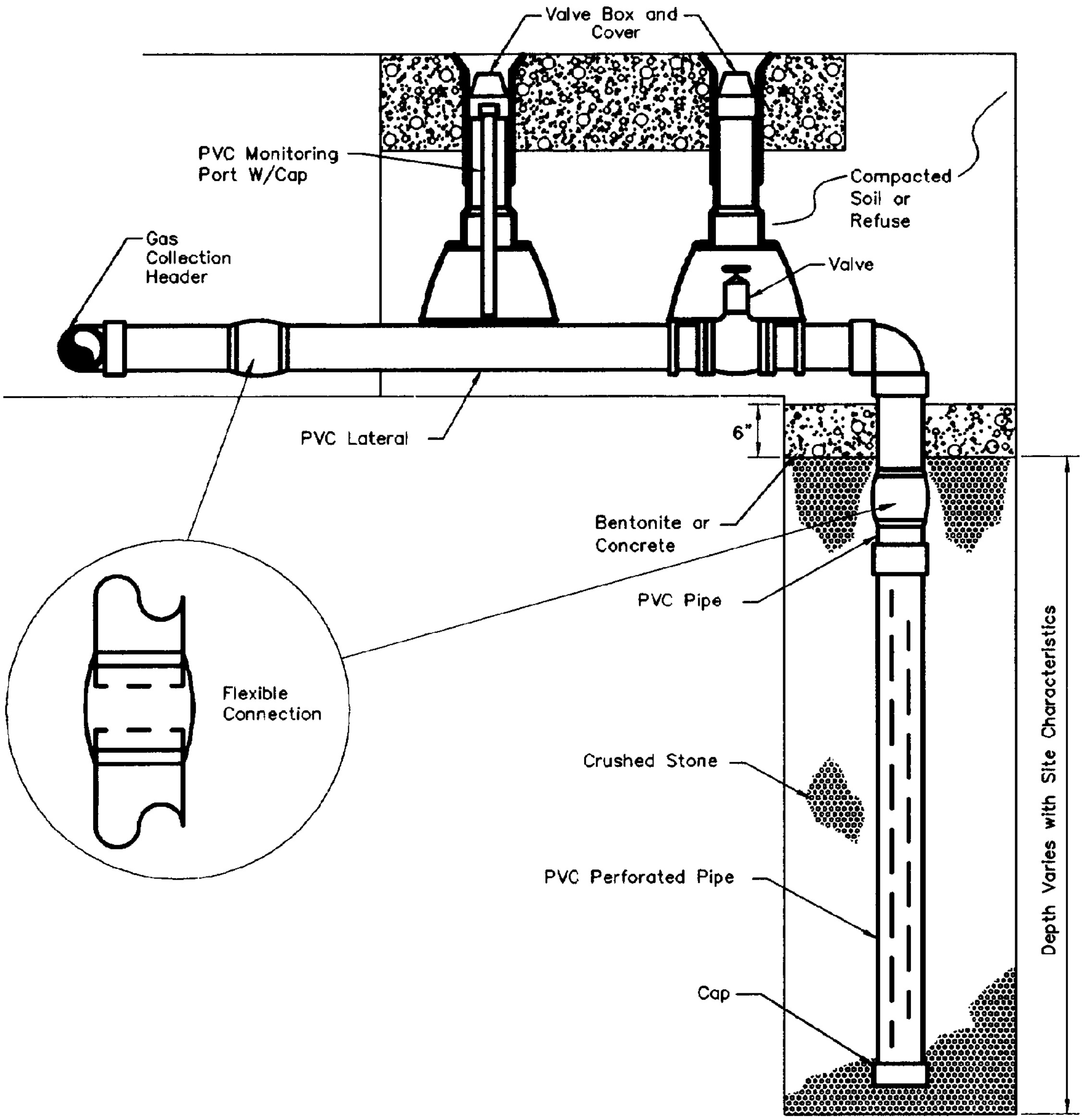
4.4.2.1 Gas Extraction Well Construction

LFG extraction wells are installed around the perimeter and into the center of the landfill. The extraction well is generally constructed of PVC, HDPE, fiberglass, stainless steel, or other suitable nonporous material. Pipe diameters vary but generally are no smaller than 5 cm (2 inches) in diameter and no larger than 30 cm (12 inches) in diameter. It is recommended that the bottom ¾ of the pipe be perforated with ½-inch-diameter holes spaced at 90 degrees every 6 inches. Slotted pipe having equivalent perforations is also suitable. Wells are typically constructed in 30 to 100 cm (12 to 36 inch) diameter boreholes. Upon insertion of the casing into the borehole, the remainder of the well excavation is backfilled with crushed stone. The crushed stone gives the extraction well a larger effective diameter from which gas can be drawn.

In unlined landfills, wells are constructed to either the base of the landfill or the water table. However, in lined landfills, wells are typically constructed to 75 percent of the landfills total depth in order to avoid damaging the liner. The screened interval of an LFG extraction well typically extends from the bottom of the well to a point at least 5 feet below the landfill surface. Slip couplings are also used for deep wells to account for differential settlement. Slip couplings should be designed to withstand circumferential pressure without collapsing. Each well head is typically designed with a butterfly or ball valve for regulating the applied pressure to the wellhead. A typical active vertical extraction well configuration is presented in Figure A-10.

4.4.2.2 Spacing and Radius of Influence

The spacing of LFG extraction wells is generally determined from the radius of influence of individual wells. This radius is described as the distance from the center of a well to a point away from the well where the steady-state-pressure gradient resulting from the blower is 0.1 inch of water. Accordingly, any CH_4 generated beyond the radius of influence would not be collected by the extraction wells.



ACTIVE VERTICAL WELL EXTRACTION WELL

FIGURE A-10
N.T.S.
(SOURCE 2)

In order to obtain a representative well spacing for the landfill, several pump tests should be performed so that waste compaction variability can be taken into consideration. Due to the costs associated with conducting these tests, there have been several theoretical models developed to estimate the vacuum-radius of influence relationship. Typical negative pressures at the well head range from about 127 to 380 mm (5 to 15 inches) of water column. Typical well spacings range from approximately 50 to 300 feet, depending on the radius of influence for each well.

The desired method for determining effective well spacing at a specific landfill is to use field measurement data. Pump tests with monitoring probes at incremental distances from the test well will indicate the influence of a given negative pressure at that location.

The EPA Methods specified in the New Source Performance Standards (NSPS) draft rule (March 1991) use Darcy*s Law to establish the vacuum/radius of influence relationship. Knowledge of both daily and final cover materials used in landfill construction, gas properties including density and viscosity, the permeability of the porous media (both the refuse and cover), and the LFG pressure are needed. Because such extensive data are rarely available or accurate, EPA has established a default maximum radius of influence of 60 m (200 feet) in revisions for publication of the final NSPS scheduled for December 1994. Use of this default parameter or the theoretical modeling is generally acceptable for estimating the radius of influence.

As noted above, use of the theoretical models based on Darcy*s Law requires estimation of several parameters. The parameters required include:

- intrinsic permeability of the refuse,
- current gas production rate of the landfill,
- static pressure at the wellhead,
- viscosity of the LFG,
- radius of the extraction well;

- length of well screen; and
- radius of influence of the well borehole.

Of these parameters, the intrinsic permeability of the refuse is the most difficult to predict. This parameter can vary several orders of magnitude between and within a landfill. This parameter has a large impact on the radius of influence predicted by the methodology. If the designer wishes to use the model for prediction of the radius of influence about a well, it is recommended that the model be used to solve the refuse intrinsic permeability to verify that the remaining parameters used predict a value for the intrinsic permeability which falls within a common range of intrinsic permeabilities for refuse ($1\text{x}10^{-7}$ to $1\text{x}110^{-12}$ cm^2).

The static pressure at the well head is the difference between landfill internal pressure and the atmospheric pressure and is the design vacuum pressure at the well head. The magnitude of the static pressure is a function of how much LFG is being produced and how impervious the capping materials are to gas migration. Where gas production rates are high and the landfill cover impervious, static pressures at the wellheads can be as high as 375 mm (15 inches) water column (wc). It is more common for wells to have static pressures in the range of 180 to 255 mm (7 to 10 inches) wc.

Viscosity of the LFG will be a function of the composition, the pressure and the temperature of the LFG. The viscosity can generally be approximated assuming the gas is composed of 50% CH_4 and 50% CO_2. At 0^{0}C and at atmospheric pressure, a 50% CH_4 and 50% CO_2 gas has a viscosity of $1.21\text{x}10^{-5}$ Pa.sec.

The intrinsic permeability can be computed as follows:

$$k_i = \frac{P_v * R^2 * \ln(R/r) * \mu_{lfg} * \rho_{ref} * Q * E_a}{M * (P_1^2 - P_v^2) * (WD/L)} \qquad (2\text{-}13)$$

where,

k_i = intrinsic permeability of refuse, cm^2 (ft^2)
P_1 = gage internal landfill pressure, Pa/m^2 (lbs/ft^2)
P_v = gage vacuum pressure at wellhead, Pa/m^2 (lbs/ft^2)
R = radius of influence, m (ft)

r = radius of well borehole, m (ft)
μ_{lfg} = viscosity of LFG, Pa.sec (lb-mm/ft^2
D_{ref} = refuse density, kg/m^3 (lb/ft^3)
Q = LFG generation rate, m^3/sec (ft^3/min)
E_a = efficiency of collection system, (1=100%)
M = Landfill capacity, Mg (lbs)
WD = Well screen length, m (ft)
L = Landfill depth, m (ft)

For the design purpose, a value of 1.0 is normally used for the efficiency, E_a, of collection system.

4.4.2.3 Number of Extraction Wells

The factors affecting the number of extraction wells selected are well radius of influence and spacing, and landfill geometry. Some overlap of influence zone is desirable for the perimeter wells of a system designed for control of gas migration to ensure that effective control is obtained at points between wells along the landfill boundary. Gas extraction rate and radius of influence are dependent on one another, and individual well flow rates can be adjusted after the recovery system is in operation to provide effective migration control and/or efficient CH_4 recovery.

4.4.3 Gas Moving Equipment

Gas moving equipment includes :

- pipeline header system, and
- compressors and blowers.

A pipeline header system conveys the flow of collected LFG from the well or trench system to the blower or compressor facility. A typical header pipe is made of PVC or HDPE and is generally 15 to 60 cm (6 to 24 inches) in diameter depending on the flow rate through each section of the pipe. The size and type of blower is a function of the total gas flow rate, total system pressure drop, and vacuum required to induce the pressure gradient.

4.4.3.1 Pipeline Header System

Collection header pipes are connected to the gas extraction wells by means of laterals constructed of flexible tubing to allow some movement between the two systems during settlement. In colder climates, the header pipe is often installed above the low permeability layer of the capping system. In warmer climates, the header system can be installed above the surface of the landfill. The exposed collection header may be subject to periodic freezing and may constitute an eyesore; however, it is very beneficial to have the pipe above ground for ease of maintenance.

Landfill settlement occurs from increased vertical stresses resulting from the refuse and cover materials and biological decomposition of the waste material. Differential settlement of the landfill can cause structural damage to the piping in the form of sags and breaks, consequently, a collector header that is not buried will be easier to repair. Other factors to be considered include the potential of vandalism and the intended end use of the site.

The basic elements in the design of the gas collection header system are the header pipe size, pipe material, pipe slope, and location of condensate traps. These will be discussed in the following sections.

Header Pipe Size. LFG headers are sized based on the design flows generated from the well system. Each section of the header should be designed to transmit the design volumetric flow rate at a velocity that will minimize friction losses and condensate losses in the header system. The first step in estimating the diameter of the header is to estimate the flow rate through each section of header. The designer can calculate these values by dividing the entire gas production potential as described in Section 4.2.2 by the total linear footage of perforated well screen for the system. This calculation will provide an estimate of gas flow rate per linear foot of pipe. The gas flow from each well can then be estimated by multiplying the length of well screen of each well by the flow rate per linear foot of screen.

The information should then be compiled on a spread sheet. The diameter of each header pipe can then be calculated using one of the following equations:

$$\text{Diameter}^{(17)} = 1.414 * (W^{0.408}/D^{0.343}) \qquad (2\text{-}14)$$

where,

W = flow rate, (1,000 lb/hr)
D = gas density (lb/ft^3)
1.414 = conversion factor

or

$$\text{Diameter}(2) = W/2000\ \text{ft.sec}^{-1}$$

where,

W = flow rate, (1,000 lb/hr)
2,000 = minimum velocity, ft/sec

In general, pipe diameters in the header system should be no less than 10 cm (4 inches) in diameter; a 15-cm (6 inches) diameter is typical. Pipe diameters as large as 325 cm (14 inches) can be installed, however, the feasibility of installing diameters of this magnitude will be a function of the allowable cover depth to prevent freezing. Pipe diameters greater than 325 cm (14 inches) are generally not used; in these cases, gas flow should be directed to a separate header line.

LFG collection systems must be designed in a manner such that condensate will not pool inside the headers. Minimum header slope must be maintained throughout the design life of the system, and landfill settlement must be accounted for in the layout of the header system. A minimum header slope of 2 percent is often used. Landfill settlement results from increased vertical stresses resulting from the refuse and cover materials and biological decomposition of the waste material. From these variables, primary and secondary settlement are calculated, and a final slope after settlement can be predicted.

The header system should be designed to allow LFG and condensate flowing in the same direction to maximize use of the heat of the gas to prevent condensate from freezing. Condensate sumps should be located at all low points in the header system to prevent clogging of the header.

4.4.3.2 Compressors and Blowers

Several types of compressors and blowers are used to remove LFG including multistage centrifugal blowers, regenerative blowers, rotary lobe compressors, and liquid ring vacuum compressors. Gas quality, peak gas flow rates, design vacuum pressure, and the pressure required for in-line processing of the gas are key parameters used to select a specific LFG compressor and blower.

Centrifugal Blowers. Centrifugal blowers are classified as constant pressure (vacuum) variable volume. The flow rates are only limited by the horse power (HP) of the motors and may be achieved across the entire performance curve from the surge point (low flow) and high flow capacity. Centrifugal blowers can be single stage, having only one impeller, or can be multistage having two or more impellers mounted in the same casing.

Single stage centrifugal blowers are typically used for applications requiring vacuums of less than 80 inches of water. These blowers are compact and produce an oil-free LFG flow. The principle of operation is as follows: Air enters the impeller in the axial direction and discharges radially at high velocity. The change in diameter through the impeller increases the velocity of the gas flow. The dynamic head is converted into static head, or pressure through a diffusion process that generally begins within the impeller and ends in a radial diffuser and scroll outboard of the impeller.

A multi-stage impeller creates pressure through the use of centrifugal force. A unit of LFG enters the impeller and fills the space between two of the rotating vanes. The LFG is thrusted outward toward the casing and then is sent to the vanes of another rotating impeller. This process continues regenerating the pressure many times until the air reaches the outlet.

Advantages of Centrifugal Blowers:

- can deliver variable volume at constant speed;
- use less power for lower flows;
- require low maintenance;
- allow for higher head pressures;
- operate on a single shaft with up to 11 impellers, typically at 3,500 rpms;
- produce a smooth, non-pulsating flow when operating at any point beyond the surge range;
- produce less noise; and
- can be equipped with auto shutdown;

Disadvantages of Centrifugal Blowers:

- surge protection is required;
- impellers will not tolerate the ingestion of large slugs of water/condensate;
- entrainment separators must be used; and
- impellers must be made of corrosion-resistant material due to the presence of H_2S in most LFG.

Regenerative Blowers. The Regenerative blower is one type of non-positive displacement and consists of a multi-stage blade impeller which rotates in a stationary housing. A unit of air enters the impeller and fills the space between two of the rotating vanes. As the blower impeller rotates, centrifugal force moves the air molecules from the root to the tip of the blade, around the housing contour, and then turned back by the annular shaped housing down to the base of the succeeding blade where it is hurled outward. This regenerative action provides staging effect to increase pressure differential which depends on the speed of the rotating impeller. This process continues regenerating the pressure until the air reaches the outlet.

Multistage regenerative blowers are available in capacity up to several hundred cubic feet per minute and typically are used for a high range of vacuum levels (180-190 inches of water).

Advantages of Regenerative Blowers:

- Is a compact unit;
- Produce an oil-free air flow;
- can deliver variable volume at constant speed;
- allow for higher head pressures;
- operate on a single shaft with up to 11 impellers, typically at 3,500 rpms;
- produce a smooth, non-pulsating flow when operating at any point beyond the surge range;
- can be equipped with auto shutdown;

Disadvantages of Regenerative Blowers:

- surge protection is required;
- impellers will not tolerate the ingestion of large slugs of water/condensate;
- entrainment separators must be used; and
- impellers must be made of corrosion-resistant material due to the presence of H_2S in most LFG.

Rotary Lobe Compressors. Rotary lobe compressors are commonly referred to as positive displacement (PD) blowers. These compressors are classified as constant-volume and variable-pressure machines. Volume can only be varied by speed change in rotating lobes via a variable frequency controller (VFC) or sheave adjustment ratio change. Rotary lobe compressors are typically used for a medium range of vacuum levels (20 to 160 inches of water). Rotary lobe compressors consist of a pair of matched impellers rotating in a stationary housing with inlet and outlet ports. The impellers, oriented in opposite directions, trap a volume of gas at the inlet and move it around the perimeter to the outlet. Rotation of the impellers is synchronized by timing gears which are keyed into the shaft.

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.

Advantages of Rotary Compressors:

- high discharge pressure at fixed flow rates.

Disadvantages of Rotary Compressors:

- Noisy,
- fixed flow rates (constant volume variable pressure;
- reducing flow rates will decrease the system pressure;
- higher compressor maintenance (oil and greasing on a regular basis), and
- Oil seals must be chemically compatible with gas contaminants.

Liquid Ring Vacuum Compressors. These vacuum pumps transfer both liquid and gas through the pump casing. Centrifugal force acting on the liquid within the pump causes the liquid to form a ring around the inside of the casing. Gas is trapped between rotating blades and is compressed by the liquid ring as the gas is forced radially inward toward a central discharge port. After each revolution the compressed gas and accompanying liquid are discharged. Vacuum levels close to absolute vacuum (i.e., absolute pressure equals zero) can be generated in this manner. These pumps generate a waste stream of liquid that must be disposed of properly. The waste stream can be reduced by recycling the liquid; however, a cooling system for the liquid stream may be needed to avoid overheating the pump. Figures A-l1, A-12, and A-13 illustrate the configuration of blowers and compressors utilized in LFG recovery systems.

Advantages of Liquid Ring Vacuum Compressors:

- can generate a vacuum level close to absolute vacuum (i.e., absolute pressure equals zero).

Disadvantages of Liquid Ring Vacuum Compressors:

- produce a waste stream of liquid that must be disposed of properly.

The gas mover (blower, or compressor) systems should be designed to handle the peak LFG flow rate over the life of the LFG project.

Sizing of a blower/compressor is based on:

- Total flow, Q_{total} for the entire landfill;
- Design operating pressure; and
- The estimated headloss in the system.

The sizing of the blower is a function of the flow rate, static pressure required at each wellhead and estimated headloss in the system. Following completion of the header layout and calculation of the header diameter, an estimation of the total

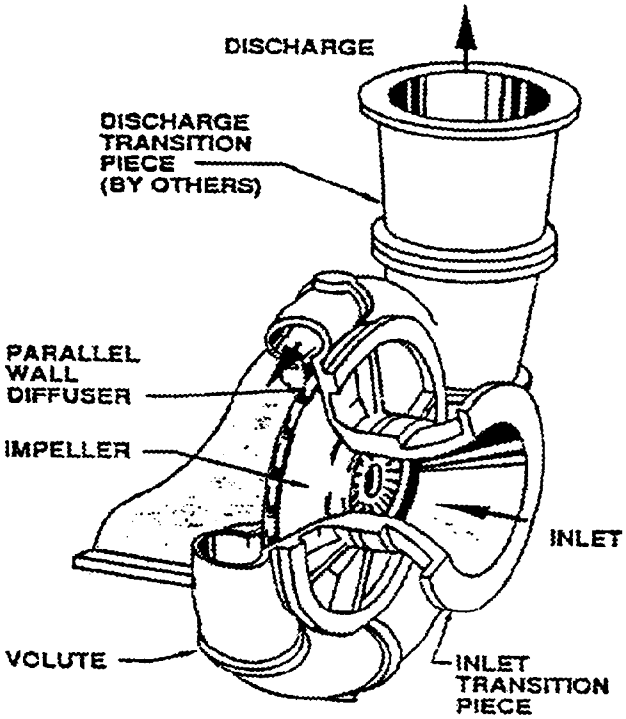


Figure A-11
Centrifugal Blower
Courtesy of Roots Dresser

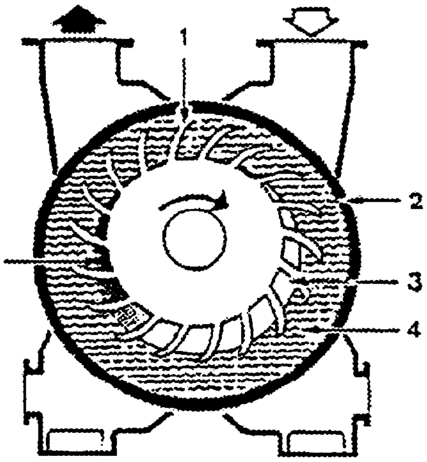


Fig. 6:31 Sectional view of a liquid-ring compressor
1. impeller
2. casing
3. intake port
4. working liquid
5. discharge port

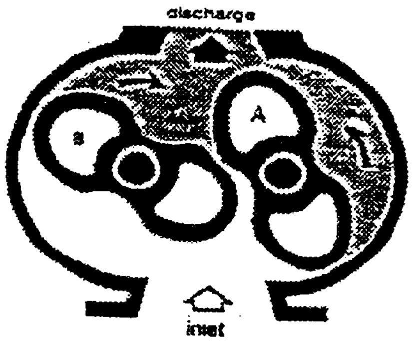


Figure A-13
Positive Displacement
Courtesy of Roots Dresser

Figure A-12
Liquid Ring Air Compressor
Courtesy of Atlas Copco

pipe losses due to friction should be computed. Methods used in the analysis of water distribution systems are used in design of the LFG collection system. Pipe losses can be calculated through the use of Darcy-Weisbach equation and the Moody Diagram(14)for friction factor in the pipe versus Reynold's number and relative roughness.

Selection of blowers should be based on the following:

- cost effectiveness;
- simplicity of installation;
- long-life expectancy;
- minimum maintenance;
- variable load capacity;
- a low gas leakage rating under operating conditions; and
- safety of operation.

Some blowers tend to leak LFG around the shaft bearing. These blowers should be limited to outdoor use only.

4.4.4 Non-Energy Recovery Systems

4.4.4.1 Flare

A flare system is used to burn the LFG in a controlled environment to destroy harmful constituents and dispose of it safely to the atmosphere. The operating temperature is a function of gas composition and flow rate. LFG composition and flow rate are variable and somewhat unpredictable with a maximum of approximately 500 Btu per cubic foot when it contains approximately 50% CH_4. Consequently, when the Btu loading derived from LFG is outside the flare design range, auxiliary fuel is required at the flare.

The elements of combustion that must be addressed in the design of a LFG flare are: residence time, operating temperature, turbulence, O_2 and flame arrestor. These elements are interrelated and, to some extent, dependent on each other. Residence time, operating temperature, and burner design must all be considered in selecting and evaluating LFG combustion equipment.

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 0_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, and solid particles, such as carbon, may require as long as 5 seconds for complete destruction.

The operating temperature of the combustor depends upon the material to be combusted. The temperature should be about 148 to 260^{0}C (300 to 500^{0}F) above the auto-ignition temperature of the waste gas. CH_4 autoignites at 540-760^{0}C (1004-1,004^{0}F), thus a minimum operating temperature of 760^{0}C (l,400^{0}F) is often specified. A temperature that is too high may cause refractory 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.

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.

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, thereby saving energy costs.

The basic flare unit consists of the following components:

- a multi-orifice burner,
- a burner chamber,
- an automatic combustion air control system (dampers),
- an electric pilot ignition system,
- sampling ports,
- flare control panel,

- temperature controller (interlock the flare stack),
- a flame arrestor, and
- emission control.

The multi-orifice burner and burner chamber are enclosed in a stack containing refractory insulation. Typical stack height of the flare is 6 to 10m (20 to 30 feet). An automatic air control system consist of dampers which operate based on the temperature controller. The dampers provide ambient air to the flare interior for combustion and for controlling the exit gas temperature. The temperature controller should have a high temperature interlock to prevent damage to the stack or personal injury. The flare, including the pilot, requires auxiliary fuel; a small propane tank is usually located near the flare to serve as pilot fuel. Sampling ports are located in the walls near the top of the stack where emissions monitoring is performed. A built-in staircase and platform are usually provided for access to the sampling areas. Stoichiometric combustion of methane has a flame temperature of 1871°C (3400°F). Insulation meltdown and internal stack explosion have occurred due to lack of excess air and high temperature interlock.

Siting of the flare is very important and should be considered in the design phase. Open flares can be located at ground level or can be elevated. Although some of these flares operate without external assist (to prevent smoking), most use steam or air, or the velocity of the gas itself, to mix the gas and air. Flares located at ground level can be shielded with a fence.

LFG is conveyed to the flare through the collection header and transfer lines by one or more blowers. A knock-out drum is normally used to remove gas condensate. The LFG is usually passed through a water seal before going to the flare. This prevents possible flame flashbacks which occur when the gas flow rate to the flare is too low and the flame front moves down into the stack.

Purge gas (N_2, CO_2, or natural gas) also helps to prevent flashback in the flare stack caused by low gas flow rate. 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 on magnetic or optical disks be used instead of paper recorder with an automatic pen to avoid maintenance problems. The total volumetric flow rate to the flame must be carefully controlled to prevent a flashback problem 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.

Another important unit independent from the flare is the flame arrestor which is installed in the LFG inlet line. The main function of the flame arrestor is the absorption of heat, thereby preventing passage of flame. The flame arrestor is packed with aluminum plates which may become clogged with the combustion by-products. Pressure gauges and sampling ports must be installed on each side of the flame arrestor to indicate clogging and necessary removal for cleaning. 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 considered for ease of cleaning and inspection.

Flares are typically designed with enclosed emission control to minimize NO_x, CO and hydrocarbon emissions while maximize the destruction of trace compounds such as vinyl chloride and aromatics. Particulate, SO_2 or HCl emissions that enter the flare will not be affected.

Thermocouples are used to monitor the flame in open and elevated flares. For the 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.

The design and selection of landfill flares depend upon the required design and operating objectives (specific emission requirements for 98% NMOC destruction efficiency). In any case, flares should be designed and manufactured to provide the minimum operating temperature under a range of LFG compositions and flow rates.

4.4.4.2 Thermal Incineration

Thermal oxidation involves heating the gas stream to a high enough temperature for combustion, typically, between 1,500 and 2,000^{0}F. Parameters affecting incinerator performance are the LFG heating value, the water content in the stream and the amount of excess combustion air. The LFG heating value is a measure of the heat available from the combustion of the VOCs in the off-gas. Combustion of LFG with a heating value less than 1.86 MJ/m^3 (500 Btu/scf) usually requires burning auxiliary fuel to maintain the desired combustion temperature. Auxiliary fuel requirements can be lessened or eliminated by the use of recuperative heat exchangers to preheat combustion air. Off-gas with a heating value above 1.86 MJ/m^3 (500 Btu/scf) may support combustion but may need auxiliary fuel for flame stability.

Combustion devices are always operated with some quantity of excess air to ensure a sufficient supply of 0_2 The amount of excess air (the amount of air above the stoichiometric air needed for reaction) used varies with the fuel and burner type but should be kept as low as possible. Using too much excess air wastes fuel because the additional air must be heated to the combustion chamber temperature. Large amounts of excess air also increase flue gas volume and may increase the size and cost of the system. The air requirement is calculated as shown below.

Each molecule of CH_4 requires two molecules of O_2 for complete combustion according to the reaction:

$$CH_4 + 20_2 -----> C0_2 + 2H_20 + heat \qquad (2-16)$$

Since air is 21 percent O_2 and 79 percent nitrogen, 9.5 molecules of air are required to supply the two molecules of 0_2. Each standard m^3 (35.7 scft) of CH_4 therefore, requires 9.5 m^3 (339 scft) of air for combustion. To ensure the reaction occurs efficiently, additional air is needed which is called excess air. Typically, a minimum of 10 to 20 percent excess air is needed to maintain a high destruction efficiency. In addition, excess air is also required to keep the reaction temperature from getting too hot. This extra air is called "quench air." As a result, the total excess air requirements may be from 100 to 250 percent above the theoretical combustion air required, depending on the operating temperatures and the CH_4 content of the LFG.

Example. Based on LFG flow of 100 cfm with 50% CH_4, 30% Co_2, 10% N_2, 10% H_20 the excess air requirements at different operating conditions are:

			Exhaust Gas Composition			
Operating Temperature C° (°F)	Exhaust Gas Flow m^3 (ft^3)	Theoretical Air %	CO_2	N_2	O_2	H_2O
			% Volume Basis			
760 (1400)	47.3 (1690)	230	4.8	74.3	13.6	7.4
982 (1800)	35.0 (1250)	140	6.4	7.29	11.1	9.6

Source: Adapted from Reference 10

Incinerators must be designed to handle minor fluctuations in flows. Packaged, single-unit thermal incinerators are available to operate on gas streams with flow rates in the range of 5.7 m^3/min (200 scfm) to about 1,430 m^3/min (50,000 scfm). However, excessive fluctuations in flow might not allow the use of incinerators and would require the use of a flare.

4.4.5 Energy Recovery Systems

The following four approaches have been adopted for recovering energy from LFG:

- upgrading the gas quality to pipeline quality for delivery to utility distribution systems;
- use of LFG directly as a boiler fuel;
- generation of electricity by the operation of an internal combustion engine with LFG; and
- use of LFG to fuel a gas turbine.

Typical LFG contains approximately 4,450 Kcal/m^3 (500 Btu/scf) of energy whereas pipeline-quality gas contains 8,900 Kcal/m^3(l,000 Btu/scf). The energy content of LFG varies widely depending upon the performance of the gas collection system and the stage of decomposition within the landfill. 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. Recent experience has shown that gas may possibly be economically recoverable from smaller landfills, especially where energy prices are relatively high.

4.4.5.1 Gas Turbines

As described in Section 3.2.2.1, two basic types of gas turbines have been used in landfill applications: simple cycle and regenerative cycle. The gas temperatures from the power turbine range from 430 to 600^{0}C (800 to 1,100^{0}F). The regenerative cycle gas turbine is essentially a simple cycle gas turbine with an added heat exchanger. Thermal energy is recovered from the hot exhaust gases and used to preheat the compressed air. Since less fuel is required to heat the compressed air to the turbine inlet temperature, the regenerative cycle improves the overall efficiency of the gas turbine.

The size of the gas turbine system is based on the potential electrical output generated by using LFG as fuel. The gas turbine system is considered to be 30 percent efficient in converting the LFG to electrical energy (3).

Commercially available steam turbines range in size from approximately 100 Kw to over 1,000,000 Kw.

Achievement of high combustion efficiency requires the controlled mixing of fuel and air and the simultaneous satisfaction of several conditions:

- air velocities in the combustor below flame speed,
- air/fuel ratio within flammability limits,
- sufficient residence time to complete reactions,
- turbulent mixing of fuel/air throughout the combustion zone, and
- ignition source to start the reaction.

A factor to be considered in turbine operation is that turndown performance is poor (i.e., the gas turbines work best at full-load, but poorly if gas supplies are less than needed to supply the full-load operation).

4.4.5.2 Internal Combustion Engines

I.C. engines are being used at landfills because of their short construction time, ease of installation, and operating capability over a wide range of speeds and loads.

Almost all larger engines used in this application are made by three manufactures: Caterpillar, Cooper-Superior, and Waukasa. These engine-generators are developed and used not only with LFG but for numerous other applications. The combustion engines are commonly turbocharged-designs that burn fuel with excess air.

Various design and operating modifications including part modifications for corrosion resistance generally allow the engines to operate successfully at landfills. Lubrication systems may also be required for combustion engines utilizing LFG fuels. Halogen compounds in the LFG decrease the pH and subsequently increase corrosion of the engine parts. Chemical additives to the oil can largely neutralize these compounds and reduce corrosion. Additionally, nonmethane VOCs can build up in the engine oil; degrading the oil and reducing its effectiveness.

Positive crankcase ventilation may serve to reduce the concentrations of these NNOC. Another potential solution is to increase the block and oil temperature to maximize evaporation and minimize condensation. Because of the severity of the oil service, frequent oil changes may be required. Oil analyses, including Total Base Number (TBN), nitration and metal content, may be utilized to determine when replacement is warranted. These analyses may also be used to predict potential problems.

Various exhaust gas catalysts are sometimes used with pipeline-gas fueled I.C. engines to reduce emission pollutants in the exhaust gas stream. Experience have proven that the acidic LFG components (halogens, H_2S) break down most of the catalysts making this technique a significant expense(15). The presence of compounds such as halogens or sulfur might require some additional equipment such as scrubbers. Scrubbers reduce acid gases and particulates in air stream by transferring these compounds to a circulating liquid stream.

4.4.5.3 Boilers

Another energy recovery option is steam-electric generation that burns LFG in a boiler to produce high-pressure steam, which then drives a steam turbine to generate electricity. The steam turbines themselves require no special modification for use in an LFG project. However, the boilers used to burn the LFG and generate the steam must have burners designed to withstand the corrosion from the H_25 and halogen compounds found in the gas.

Other parameters which should be considered in the design of steam turbine plant are:

- relatively clean water supply is needed for make-up, and
- accommodation to the variations of LFG composition without major adjustment to the combustion control system.

4.4.5.4 Potential Future Technologies

Several potential technologies are under development to improve LFG application: these include future flare design using low Btu's LFG 15 percent CH_4 with air regulation and long detention time, fuel cells, vehicular fuel, and possibly synfuels production.

Fuel cells are essentially electrochemical batteries. Fuel cells have been well established as a technology for generating energy for more than 20 years using natural gas. They are currently being considered for LFG applications in large municipal landfills (1,6).

Vehicular fueling with compressed CH_4 is of high interest for environmental and other reasons. Using LFG would involve some purification, possibly to near pipeline quality. The vehicle would have to be equipped with conversion kits, which include safety devices, to manage the high pressure involved.

Synthetic liquid fuels production is another application for LFG. Available technologies that could convert LFG to liquid fuels include hydrocarbon production by Fischer-Tropsch, methanol synthesis by various routes, including chemical catalysis at high pressures, or by partial biological oxidation(1).

4.5 GAS CONDENSATE SYSTEM COLLECTION AND CONTROL

Condensate management should be one of the key design elements of a LFG system. Condensate from LFG operations is classified as non-hazardous waste unless it exhibits a RCRA hazardous characteristic or is derived from RCRA listed wastes.

If LFG condensate is considered as a hazardous waste, the condensate cannot be returned to the landfill from which it was derived unless first treated.

Condensate characteristics are site specific. Since the regulations that apply to condensate management vary, the management options available at each facility will be based on state laws, restrictions of the local wastewater treatment plants, and other local decisions.

Water scrubber or knockout vessels are often used in control/recovery systems to remove liquids, primarily to prevent corrosion or line freeze-ups. If the condensate is not removed, it will collect in the lower portions of the system and plug the pipes, blocking the passage of gas and rendering the extraction system ineffective. Condensate sumps and traps must be designed to continuously drain condensate from all transmission lines under both negative and positive operating pressures while maintaining a seal between the gas stream and the atmosphere. A check valve may also be used at the outlet of the trap to prevent air or water flow back into the pipe. Water traps should be designed to withstand a minimum of 12 inches of water column more than the anticipated design vacuum in the system. Generally, condensate traps should be placed at the lowest points in the collection header system.

Condensate sump pumps usually have intakes above the motor casing and do not tolerate being pumped dry for long periods, the condensate collection sumps are rarely pumped completely dry. As a result, some water is always present in the sump and potentially in the conveyance system.

Condensate may also be managed by avoiding its formation. After initial condensate knock-out, the gas may be heated to avoid condensation in the lines or treatment equipment.

The temperature and moisture content of the extracted LFG and the ambient air temperature will impact the volume of the condensate that is produced from the extracted LFG. If pump tests are performed to establish the radial influence caused by various vacuum pressures, samples of the LFG can be collected and analyzed for moisture content and temperature. If pump tests are not conducted, estimates can be made assuming the LFG is saturated with moisture. This assumption will yield a conservative estimate for condensate generation as most operating LFG collection systems do not produce volumes of condensate predicted by assuming a saturated gas. Temperature of the gas can be measured by inserting probes into the landfill. Temperature of the LFG can also be estimated based on literature values for landfills similar in composition, age and dimension. Temperatures for the minimum ambient conditions that could occur in the piping system located above the low permeability liner can be estimated by surveying the climatological records for the geographic area. Temperature estimates for buried pipes can be estimated by contacting the local Soil Conservation Service and obtaining soil temperatures with depth for the region. Neither of these ambient temperatures will necessarily be the temperature that will be observed in the header system due to the heat content of the LFG, however, these temperatures represent a conservative approximation.

The calculation of condensate generated by cooling of LFG saturated with condensate can be approximated by assuming that condensate is similar in density to water and LFG is similar to air. This assumption permits use of psychometric charts developed for properties of steam. Using tables from psychometric charts, an estimation of the concentration of water (condensate) in air (LFG) can be made by dividing the humidity of the moist air by the specific volume of the moist air for the ambient temperature in the piping system as described in the preceding paragraph. This water concentration represents the concentration that will remain in the gas stream after cooling. The same calculation is made for the temperature corresponding to the temperature of the LFG. The volume of the condensate is then estimated by multiplying the water concentration at each temperature by the flow rate to determine the volume of condensate present in the gas stream at each temperature. The volume of the condensate is then estimated by subtracting the volume of condensate that will remain in the gas stream (ambient temperature) from the volume of condensate that exists in the gas stream at the temperature of the gas as it is extracted from the landfill.

Since LFG is seldomly saturated and the ambient temperature in the header system is usually higher than the ambient temperature of the surrounding soils or air, the volume of condensate computed by this method is conservative. This method generally over-predicts condensate generation rates. If a greater degree of accuracy is needed, it is recommended that a thermodynamic balance of the system be conducted. Since this level of accuracy is typically not needed for landfills, the methodology for this calculation is not presented in this document.

Condensate flow from gas collection piping is relatively low. In the northwest, condensate flows average approximately 0.015 gpm/acre of landfill. Due to low flows, the condensate collection piping (from gas header) is quite small and the pipe is usually sized based on cleaning equipment.

Removal of condensate in a knock-out pot is caused primarily by a pressure drop. The amount of condensate that will form from a pressure drop can be estimated as follows:

$$Q_{cond} = \frac{0.0203\ Q_{TOT}}{760 - 1.87 \Delta P_{TOT}}$$

where,

Q_{cond} = flow rate of condensate, m^3/min
Q_{TOT} = total gas flow rate, m^3/min
ΔP_{TOT} = total pressure drop, N/m_2

An alternative method to collect condensate is using a vacuum valve station (VVS), condensate collection tank and vacuum pump(16). The VVS is installed between the gas and condensate collection manifold. Condensate from the gas header first fills the VVS, which acts as a float trap, to a point where an internal float ball opens a needle valve. When the needle valve is opened, the condensate is sucked from the VVS into the condensate manifold which drains into a condensate collection tank. An inverted stainless steel air release valve (as manufactured by APCO) is used at the VVS as the float trap. A vacuum pump is used to create the vacuum in the condensate collection tank and the entire condensate collection manifold. Deep well ejector pumps are used to pump the condensate from the collection tank into the next disposal system.

There is no comprehensive database on the chemical and physical characteristics of LFG condensate. 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 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. Since most condensates do not have two phases, only aqueous phase disposal issues are discussed in this document.

Disposal of gas condensate is an issue common to most landfill sites in humid climates. Methods of disposal for LFG condensate include:

- disposal at a local publicly owned treatment works (POTW) through municipal sewer lines or tank trucks,
- on-site treatment,
- injection of condensate back into the landfill, and
- aspiration of the condensate into an LFG flare.

Disposal at a local POTW depends on the physical and chemical characteristics of the condensate and the POTW's permit requirements.

Condensate recirculation is being practiced at numerous sites and is accomplished primarily through drainage into the collection well field at moisture traps, although this practice runs counter to conventional land practice. The return of condensate to the landfill will not be allowed unless the landfill is equipped with a composite liner and a leachate collection system (40 CFR Part 258).

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.

These are discussed in the previous sections.

Quenching 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 at 870^{0}C (1600^{0}F) upon aspiration into the flare chamber. 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.

The operating efficiency of a gas flare is based on the turbulence condition. The aspiration of condensate will cause a change in the turbulence conditions inside the flare chamber.

4.6 ELECTRICAL

Electrical system design includes requirement for materials, equipment, and installation. Any future power needs that may be anticipated should also be included. In addition, reference codes, standards, specifications and area classifications should be used.

4.6.1 Codes. Standards, and Specifications

Codes, standards, and specifications include:

American Petroleum Institute (API)

- RP500 A -Recommended Practice for Classification of Areas for Electrical Installations in Petroleum Refineries.
- RP500 B -Recommended Practice for Classification of Areas for Electrical Installations at Drilling Rigs and Production Facilities on Land and on Fixed and Marine Platforms.
- RP500 C -Electrical Installations at Petroleum and Gas Pipeline Transportation Facilities.

American National Standard Institute (ANSI)

- C2 National Electrical Safety Code.
- C80.l National Electrical Safety Code Specification for Rigid Steel Conduit, Zinc Coated;
- C80.5 Specifications for Rigid Aluminum Conduit.

National Fire Protection Association (NFPA)

- 30 Flammable and Combustible Liquid Code
- 70 National Electrical Code (NEC)
- 496 Purged and Pressurized Encloses for Electrical Equipment in Hazardous Locations
- 497 Class I hazardous Locations for Electrical Installations in Chemical Plants.

Institute of Electrical and Electronics Engineers (IEEE)

- 141 Recommended Practice for Electrical Power Distribution for Industrial Plants;
- 518 The Installation of Electrical Equipment to minimize Electrical Noise Input to Controllers from external sources.

4.6.2 Areas Classifications

Classifications. A general rule is that the electrical components are not to operate in an explosive atmosphere. Whenever feasible, electrical equipment should be located in non—hazardous areas.

The areas to be classified fall into one of the following types as established for electrical installations in the NEC (NFPA 497):

Class I. Division I. Group D.

Class I, Division I, Group D are applied to locations where flammable gases or vapors, such as CH_4, are likely present in normal operating conditions.

Class I. Division 2. Group D.

Class I, Division 2, group D are applied to locations where flammable gases or vapors, such as CH_4, are normally confined and the flammable gases are present only in case of abnormal operation of equipment or in case of accidental rupture of pipe/container.

Unclassified Locations.

Unclassified areas fall into the following categories:

a. Locations that are adequately ventilated where flammable substances are suitably contained in well maintained closed piping systems which include only pipe, valves fitting are considered nonhazardous; Locations that are not ventilated, and piping systems inside do not have valves, fittings or other appurtenances are considered as nonhazardous.

b. Locations containing permanent sources of ignition, such as fired boilers, pilot lights, equipment with extremely high surface temperatures (above ignition point of the gases in the area) are not deemed hazardous.

4.6.3 Conduit Seals

Conduit seals are required on underground conduits between the ground surface and panels or equipment where sparking components are located.

4.6.4 Electrical Enclosures

Enclosures include power panels, control panels and other similar enclosures. According to NFPA 70-501-15, there shall be no exposed live parts (conduct electricity). In Class I locations, all live parts must be housed inside enclosures. Enclosure information is provided by the National Electrical Manufacturers Association (NEMA).

Non-explosion proof blower control panels may be mounted on an outside wall, or in a separate control room where positive pressure ventilation is maintained. Explosion proof equipment should be used on inside walls of the blower buildings.

4.6.5 Motors and Generators

Standards for motors and generators are provided by NEMA in ANSI/NEMA Standard MG-l. In LFG applications, all motors are to be enclosed. These include:

- Totally-enclosed nonventilated (TENV);
- Totally-enclosed fan-cooled (TEFC); and
- Explosion proof.

4.6.6 Installations

Electrical installations should be in accordance with API RP 540 and the NEC or local codes where applicable.

4.6.7 Grounding

All electrical systems require a reliable effective grounding system. Wiring and equipment in Class I, Division 2 locations must be grounded as specified in the NEC, latest edition.

4.7 SYSTEM MONITORING

A monitoring program should be established at all solid waste landfills. The monitoring program may be different depending on the end use of the LFG. Typically, in a landfill with blower/flare stations, the following areas need to be monitored:

- gas wells,
- collection system,
- condensate,
- flare, and
- LFG migration monitoring.

The following sections discuss monitoring parameters of each area, including locations, frequency, and monitoring activities associated with each.

4.7.1 Gas Wells

Following are monitoring parameters associated with gas wells:

4.7.1.1 Monitoring Locations

Monitoring locations at the wells should be established at the wellheads to monitor the LFG quality and quantity.

4.7.1.2 Frequency

The frequency of monitoring and adjustment is a site-specific determination based on how stable the system is. If the landfill cover is leaking and the system shows signs of air intrusion, the system requires weekly monitoring and adjustment. More stable systems may require monitoring and adjustment on a monthly or even less frequent basis.

4.7.1.3 Valve Position

A continuous record of the position of the valve regulating the vacuum applied to a wellhead should be kept as observed during routine inspection and maintenance. The valve position should be modified if monitoring parameters indicate that ambient air is intruding into the zone of influence for the well.

4.7.1.4 Gas Quality - Chemical

Methane. CH_4 content should be measured as an indicator of the quality of the LFG being extracted by the well. For a municipal solid waste landfill, measurements below 50 percent by volume may be an indicator that ambient air is intruding into the zone of influence of the well. This condition together with other parameters will help determine if the vacuum applied to the wellhead should be modified by altering the valve position. It is most common to measure CH_4 in units of “percent by volume” of gas. In MSW landfills, measurement of less than 45 percent CH_4 by volume should be used as the lower limit for modifying the valve position to reduce the opening.

CH_4 can be monitored through the sampling port on the wellhead using a hand-held instrument. New instruments which use infrared absorption to detect CH_4 concentrations are becoming available. The accuracy of these instruments are limited to ± 5 percent.

Oxygen. 0_2 is measured as an indicator of ambient air intrusion. 0_2 in the LFG should be in the range of 0 to 2 percent by volume. 0_2 levels in excess of 2 percent may be indicative of ambient air intrusion into the system. It is important to monitor 0_2 both as an indicator of ambient air intrusion and also as an indicator of the decomposition conditions in the landfill.

Portable O_2-sensing meters are typically used to monitor the O_2 content of the gas as sampled through the sampling port in the wellhead. Precaution should be taken in the calibration of these instruments as the sensitivity of the instrument is generally ±2 percent and a poorly calibrated instrument may lead to incorrect conclusions regarding well performance.

Carbon Dioxide. CO_2 is monitored to assess the condition of the landfill. Concentrations of CO_2 in excess of the concentration of CH_4 may be indicating that the landfill is not operating anaerobically. This condition is known as composting; composting can lead to landfill fires. The potential for composting conditions should be monitored by calculation of the composting ratio as shown in Section 4.7.1.6.

Many of the infrared devices developed to measure CH_4 can also be used to measure CO_2. Samples can be obtained directly through the sampling port in the wellhead.

4.7.1.5 Gas Quality - Physical

Pressure. Pressure should be measured at the wellhead sampling port in inches of water column (in. wc). One pound per square inch (psi) pressure is equal to 27.7 in. wc pressure. Gauge pressures should be recorded as negative indicating the pressure is less than atmospheric. Wellhead pressures significantly different than system pressures may be an indication of localized flow blockages.

Pressure is typically monitored using a magnehelic-type analog pressure gauge or hand-held pressure transducer gauge. Care must be taken to insure the monitoring instrument can measure anticipated pressures. Typical pressures at the wellhead range from -0 in. wc to -10 in. wc.

Temperature. If excessive ambient air is being pulled into the well, the temperature of the gas stream may decrease. The magnitude of the decrease will be dependent on the difference between the ambient temperature and the temperature of the gas within the landfill. Due to the difficulty in assessing these differences, temperature should be used in combination with other parameters as an indicator of ambient air intrusion.

Temperature is typically measured using a thermocouple attached to a digital-readout instrument.

Flow Rate. The flow rate is the measurement of the volume of gas flowing through the well per unit time. The flow rate is typically monitored to evaluate the flow at an individual wellhead in conjunction with CH_4 content and pressure to assess if control valve modifications are necessary. Since flow rate is dependent on temperature and pressure, it is important that both of these parameters are measured at approximately the same time as the flow rate measurement. Notation of these parameters will permit conversion of field data to standard conditions if needed for system evaluation.

Flow rate is typically calculated from measurements of the velocity of the gas and knowledge of the cross-sectional area of the pipe. Pitot tubes are the most common measuring device, however, some inaccuracy is imparted due to the moisture content of the gas. Thermal-mass flow indicators are also used to monitor flow rate. Both instruments can be used with the sampling ports installed at the wellhead.

Use of thermal-mass flow instruments requires that the density and heat carrying capacity of the gas stream is known. Since different locations of a landfill may generate different gas compositions, hence different density and heat carrying capacity, gas composition of different locations should be analyzed, and a chart of density and heat carrying capacity should be made. This chart should be used to adjust the difference in density and heat carrying capacity according to the manufacturer*s recommendations when thermal-mass flow instrument is used.

4.7.1.6 Analysis of Data

Following collection of data, calculations of several indices should be made in the field to assess overall system operation and landfill conditions.

Methane/Carbon Dioxide. The ratio of CH_4 to CO_2 should always be one or slightly greater than one. This index can be used to quickly assess ambient air intrusion. For example, a CH_4 to CO_2 ratio of 0.80 indicates that about 20 percent of the gas produced may be originating from aerobic decomposition or leaks in the landfill cover instead of anaerobic decomposition.

Composting Ratio. This ratio considers both O_2 and CH_4 in estimating the probable amount of air flow that results from ambient air intrusion. The ratio is:

$$\text{Composting Ratio} = \frac{\left(\frac{1-\%CH_4}{57}\right)*0.21 - \left(\frac{\%O_2}{100}\right)}{\left(\frac{1-\%CH_4}{57}\right)*0.21 - \left(\frac{\%O_2}{100}\right) + \left(\frac{\%CH_4}{57}\right)} \tag{2-16}$$

The maximum allowable value of the composting ratio reported, prior to taking action to improve conditions supporting anaerobic biodegradation, is 8. Higher values indicated that anaerobic processes are being impacted by O_2 intrusion. Immediate measures should be taken to determine where O_2 intrusion is occurring.

4.7.2 Collection System

The objective of operating the gas collection system in a landfill is to maximize gas collection. This is achieved by having a well balanced vacuum in all parts of the system so gas is collected as possible without drawing air in through the landfill cover. Monitoring data will reveal how far out of balance or how much air is pulled into the system. The monitoring data can be used to determine adjustments required to achieve the operating goal.

This section describes the location, frequency and methodology for monitoring activities associated with the collection system.

4.7.2.1 Monitoring Locations

Monitoring points should be established at several locations in the collection system, for example at each gas well and at the inlet to the blower, to permit evaluation of the gas quality for discrete sections of the LFG collection system. Monitoring points are established so as to help isolate any blockages in the system.

4.7.2.2 Frequency

The frequency and schedule for monitoring points in the collection system are similar to that of the gas wells. These points should also be monitored as system operations indicate potential blockages in the collection system.

4.7.2.3 Gas quality — Chemical and Physical

Monitoring chemical gas quality in the collection system is the same as described for the gas wells.

4.7.3 Condensate

This section describes each of the units in the condensate management system and the monitoring requirements associated with each unit.

4.7.3.1 Remote Sumps or Tanks

To collect the LFG condensate from pipe headers, remote sumps or tanks are typically positioned at various locations in the LFG collection system. Each sump or tank is equipped with pumps (submersible or above ground). These sumps are fitted with high liquid level alarms as well as pump on/pump off level controls. The pumps should be inspected as part of the monthly inspection program to ensure that there are no obvious signs of irregular wear.

The control panel for each sump typically includes:

- a high liquid audible or visual alarm,
- moisture sensors, and
- a temperature limiter.

The control panel operation should be inspected and verified. Manufacturer*s recommended maintenance plan for the pumps and control/alarm systems should be implemented into the monitoring plan, and any routine observation requirements should be included in a monitoring log.

The condensate force main should be monitored monthly. The flow meters located at the sump pump discharges should be monitored to insure that there is no loss of flow between two monitoring points which would be an indicator of a potential leak in the main. Observation of the condensate flowmeter should be recorded on the monitoring log established for the sump inspection.

Spare parts for pumps should include one mechanical seal set per sump pump. As the spare seals are utilized during routine O&M, spare seals should be replenished at the site.

4.7.3.2 Central Units

Knock-out Pot. The knock-out pot will remove any moisture entrained in the LFG stream prior to the blower. The knock-out pot has no mechanical parts and therefore requires minimal monitoring. Monitoring should include inspection of the discharge lines to insure the lines appear in good condition and permit free drainage to the condensate storage tank. Valves permitting free-flow of the condensate from the knock-out pot to the storage tank should be maintained in the open position to prevent build-up of condensate in the knock-out pot.

4.7.4 LFG Migration Monitoring

4.7.4.1 Locations

Gas migration should be monitored both laterally and vertically. These include the following:

- spacing for probes,
- probes depth, and
- sampling frequency

Lateral migration monitoring is achieved by installing permanent gas monitoring probes at the periphery of the landfill to check for potential subsurface landfill gas migration is not escaping the landfill boundary.

Vertical migration is monitored across the surface of the landfill by moving portable instruments across the landfill. Locations where instruments measure concentrations above background will be noted and investigated further to check for vertical migration/outgassing.

4.7.4.2 Gas Quality - Chemical

Methane. CH_4 should be monitored as described in Section 4.7.1.4.

Carbon Dioxide. $C0_2$ should also be monitored if CH_4 is observed in order to determine if the CH_4 being monitored is the result of LFG migration or natural processes. Methods of monitoring $C0_2$ are discussed in Section 4.6.1.3.

4.7.4.3 Gas Quality- Physical

Temperature. Temperatures within a landfill are normally higher than ambient temperatures. Temperature measurements are most useful when compared over time, to determine if a rising or falling trend of LFG production is occurring. High-temperatures also indicate aerobic reactions which are occurring due to air infiltration into the landfill.

Pressure. By measuring the pressure, the operator know how well the system is balanced ,i.e., if he is achieving the same pressure differential at all collection points. Monitoring the barometric pressure when monitoring LFG is helpful in reducing and interpreting data. Barometric pressure should be measured using a manometer or similar instrument.

4.7.5 Flare System and Appurtenances

This section describes monitoring requirements associated with each unit in a blower/fare system.

4.7.5.1 Blower

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 gauges at the entrance- and exit-way to the blower at ports included in the piping system to ensure that parts of the blower assembly have not worn or are causing excessive head loss across the unit. The blower should also be inspected and monitored according to manufacturer's specifications for the unit.

Frequency. It is recommended that monthly inspections be made, unless recommended otherwise by the manufacturer, to insure 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 ascertain that no parts are wearing at a rate that is not expected. Should the equipment warranties recommend more frequent inspection, this frequency should be upgraded to the recommended levels.

4.7.5.2 Flame Arrestor

Monitoring Requirements. Monitoring of the flame arrestor consists of measuring the head loss across the flame arrestor to insure 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.

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

4.7.5.3 Flare Unit

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

- gas-flow rates;
- gas supply pressure;
- minimum operating temperatures; and
- influent gas parameters including CH_4, CO_2, and O_2.

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. If there is insufficient pressure, the blower should be inspected as noted in Section 4.7.5.1.

Minimum operating temperatures are generally specified by manufacturers to be 1,400^{0}C. The temperature of the flare unit should be inspected to insure 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. > l,800^{0}C) are observed, controls for these louvers should be inspected.

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.

Frequency. Additional operating parameters including gas flow rates; gas supply pressure; minimum operating temperature; and inflow LFG parameters should be monitored more regularly. Monthly monitoring is recommended unless suggested otherwise by the manufacturer.

4.7.6 Automation of Controls

Generally, there are the following three forms of process control: local control, centralized control, and remote control. 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 by means 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 also easier to operate. Centralized data acquisition and control may include the use of computers or PLCs. 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. Therefore, if extensive future modifications to the proposed system may be anticipated, hard-wiring the process logic should be avoided.

Modems and radio telemetry can be used to control these systems remotely. Radio telemetry is typically used over shorter distances when radio transmission is possible. Modems are used with computerized control systems. Systems can also be equipped with auto dialers to alert the operator of a malfunction by telephone or pager.

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 section will present:

- control elements used in the design,
- different degrees of automation,
- a list of minimal acceptable components, and
- a description of special instrumentation that may be used in these systems.

4.7.6.1 Control Elements

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 issues with known compounds in certain landfills.

Methane Gas Detectors. Gas detectors may be placed in the feed manifold system of either active or passive collection systems to monitor the explosive range (or Btu content) of the recovered gas. Systems which burn the gas have different operating target values than systems which vent or otherwise dispose of it. The detectors may measure specific CH_4 (and other gas) content, using a GC; Combustible Gas Indicators (CGI), which measure the percent of lower explosive limit (LEL) of the gas being processed; or FID, which measure the concentration of VOCs relative to a calibration gas (which may be CH_4). The type of detector selected depends on the objectives of collection, whether the fuel value is to be recovered, and safety considerations for the landfill.

Alarms. The gas control system will usually require several alarms to ensure safe and efficient operation. As described above, alarms must be provided to ensure the water collection system does not overflow into the blower train. Alarms are required to alert for too rich a feed in the explosive range, or perhaps 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. 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 which serves the blowers or pumps in the form of thermal overload systems, circuit breakers or fuses to indicate when these systems have tripped.

Control Panel Layout. A control panel layout must be designed. This drawing will show, to scale, all electrical components and the associated wiring. Depending on the project, this control item may be submitted as a shop drawing by the instrumentation and control contractor. For example, the control panel for the condensate sump should include a high-liquid level alarm bell and the light; moisture sensors; temperature limiter, etc..

Logic Diagram. A logic diagram must be included if the process control logic is not apparent from the Piping and Instrumentation Diagram (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 the LFG is too rich, then the blower will be turned-off to prevent explosion situations in the flare.

The set of documents must have a legend to explain the symbols that are used. Regardless of the existence of the legend, standard symbols must be used wherever applicable.

4.7.6.2 Degree of Automation

The degree of automation is generally dependent on the complexity of the off-gas treatment system (if any), the remoteness of the site, and monitoring and control requirements. Typically, a trade-off is required between the initial capital cost of the 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.

4.7.6.3 Minimum Acceptable Process Control Components

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, and
- explosimeter for sites with recently measured LEL levels greater than 10 percent.

O_2 monitoring and feedback controls are required on low emission engines. Automatic control of the stoichiometric ratio is by far the preferred method for long-term operation of LFG fired I.C. engines.

4.7.6.4 Special Instruments

Several specific instruments are common to the LFG control system that should considered in the design. These include:

- portable CH_4 and combustible gas meters (such as those originally developed for the natural gas industry and for mine safety),
- instruments that use infrared absorption for CH_4 measurement, and
- process GC.

CH_4 and combustible gas meters operate on two different principles. Both indicate the presence of any combustible gas, and need to be calibrated using CH_4 gas. Calibration should be performed according to the manufacturer's instruction.

Instruments that use infrared absorption have been developed specially for monitoring LFG. They operate on the principle that CH_4 strongly adsorbs light at certain wavelengths in the infrared range (> 400nm).

Process GC are used for onsite monitoring and control. However, laboratory facilities and trained chemists are required for monitoring operation.

4.7.7 Other Design Considerations

Other design parameters include:

4.7.7.1 Site Working Areas

Special working areas should be designated on the site plan for other contingency situations. Access areas to the landfill should be provided for checking the pipe headers, well heads, condensate traps and sumps. Arrangements for working areas may include locating such areas closer to the entrance gate. working areas are site specifics.

4.7.7.2 Office Buildings

At larger landfills where climates are extreme, a building should be provided for office space and employee facilities. Sanitary facilities should be provided for landfill personnel. At smaller landfills, trailers may be sufficient.

4.7.7.3 Utilities

Large landfills will need electricity, water, air, 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.

4.7.7.4 Emergence Power

All LFG's extraction systems should be equipped with emergency power sources such as generators. To keep the blowers operating continuously, the generators should automatically turn on if the power supply falls below a certain voltage to avoid extensive buildup of potentially harmful or explosive gases in the event of a power outage.

4.7.7.5 Air

In the case where compressors are used to pressurize the extracted gas for combustion, an air supply will be needed for instrumentation control.

4.7.7.6 Water

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

4.7.7.7 Fencing

At some sites, it is desirable to construct perimeter fences to keep out any trespassers or animals. If vandalism and trespassing are to be discouraged, a l.8-m (6-foot) high chain link fence is desirable. A wood fence or a hedge may be used to screen the operation from view. Locking vault covers and security guards may be required, in some areas to deter vandalism.

4.7.7.8 Lighting

If the landfill has structures (employee facilities, administrative office, equipment repair, or storage sheds, etc.) or if there is an access road in continuous use, permanent security lighting may be desirable.

4.7.7.9 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 facilities, 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. A flare station may be left unattended, the computer maintaining the control system will shut down the collection system and notify the facility's off-duty operator via a dialer in case of malfunction.

4.7.7.10 System Safety

Due to the explosive nature of CH_4 gas, processing station electrical equipment and fixtures shall be typically classified as Class 1, Division 2, Group D of the NEC. Guidelines for Safety are presented in Article 501 of the NEC. For "Intrinsically Safe Systems” Article 504 of the NEC is recommended. Some local codes may be more restrictive than the aforementioned and should be examined before design.

If flares or burners are employed, flame arrestors should be installed in the inlet lines. Flame arrestors provide a means of reducing potential explosion hazards by preventing flashback of combustion gases from the burner through the process station.

5.0 REGULATORY REQUIREMENTS

This chapter discusses air toxics rules under the CAA, local air toxics rules, and proposed global warming legislation.

5.1 SUMMARY OF APPLICABLE REGULATIONS

Regulations affecting LFG management are addressed under various legislation including:

- the RCRA which regulates solid waste management such as the landfill itself,
- the CAA which regulates air emissions, and
- the Clean Water Act (CWA) which regulates discharges of water such as LFG condensate.

In addition to these federal regulations, similar state or local regulations may apply. A brief summary of potential regulations applicable to LFG management follow.

5.2 RCRA REGULATIONS

5.2.1 40 CFR 258

Under RCRA Subtitle D authority, rules were promulgated October 9, 1991 which described minimum federal criteria for MSW landfills. Part 258 of that rule was also co-promulgated under the authority of the CWA. RCRA regulates LFG from MSW landfills under 40 CFR Part 258 which states that owner/operators of NSW landfills must ensure that the concentration of CH_4 gas generated by the facility does not exceed 25 percent of the LEL for CH_4 in facility structures (excluding gas control or recovery system components) or the LEL at the facility property boundary. The owner/operators must also implement a routine CH_4 monitoring program with at least a quarterly monitoring frequency.

Section 258 additionally requires owners/operators of MSW units to comply with applicable requirements of the State Implementation Plans (SIPs) developed under Section 110 of the CAA.

5.2.2 40 CFR 261

Additional RCRA regulations pertaining to characterizing or managing hazardous wastes may apply where a landfill site generates gas condensate if the condensate is managed or disposed of as a waste. The condensate may be considered a hazardous waste unless testing demonstrates that none of the characteristics of ignitability, corrosivity, reactivity, or toxicity are present in accordance with EPA analytical methods.

Condensate may also be a hazardous waste if it is specifically listed as a waste in 40 CFR Subpart D. Listed wastes may be from non-specific sources (F001-F012, F019-F028, F032, F034-F035, F037 and F039) such as spent non-halogenated solvents (FOOS) or from specific sources (K00l-K151) such as spent carbon from treatment of wastewater containing explosives (K045). Listed wastes also include commercial chemical products or manufacturing intermediates which are identified as acute hazardous wastes (P001-P022), i.e., tetraethyl lead (P110) or which are identified as toxic wastes (U00l-U248),i.e., benzene (U019). In general, landfill gas condensate would not be considered as a listed waste.

Due to substantial water content, condensate is generally not corrosive (pH less than 2 or greater than or equal to 12.5 and a steel corrosion rate of 6.35 mm per year) or reactive (contains reactive sulfides or cyanides, reacts violently with water or is capable of detonation). Condensate may be ignitable (flash point less than 140^{0}F) if sufficient material has accumulated to separate into an aqueous phase and a hydrocarbon phase (0.5 to 5% of the total volume). Condensate in an emulsified state is not likely to be ignitable. Condensate would be considered toxic if the concentrations of listed contaminants exceed regulatory limits after a leachate preparation.

If testing demonstrates that condensate is characteristically a hazardous waste, the Universal Treatment Standards (UTS) may be applicable. The required treatment standards for these wastes must be met and the treater has the option of disposing of the treated wastes in a Subtitle C or Subtitle D facility. Waste derived from a listed waste cannot be disposed of at a subtitle D facility unless formally delisted.

5.3 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 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. Potential applicable regulations include:

- New Source Performance Standards (NSPS),
- National Emission Standards for Hazardous Air Pollutants (NESHAPS),
- Title III of the CAA Amendments (CAAA), and
- Title V of the CAAA.

Each of these are described in more detail in the following sections.

5.3.1 NSPS

The primary rules affecting LFG operations from the 1970 CAA are the NSPS. In general, these regulations apply to municipal landfills and require the collection and control of CH_4 and NMOC, collectively called "LFG."

The NSPS rules apply to municipal landfills and are addressed in 40 CFR Parts 51, 52, and 60. Proposed rules were published in the Federal Register on May 30, 1991 with additional data and information on changes in EPA's modeling methodology were published in draft form on June 21, 1993. The proposed standards are scheduled for promulgation in September 1994 but have not been promulgated at the time of the preparation of this document.

The proposed rule would required LFG emission control at landfills that:

- receive MSW,
- received waste after November 8, 1987,
- exceed a maximum design capacity of 100,000 metric tons (Mg) of in-place refuse, and
- exceed a maximum NMOC emission rate of 150 Mg per year.

To avoid installation of an LFG control system, the landfill must demonstrate that the emission limit would not be exceeded. This demonstration requires the calculation of the NMOC emission rate by:

- performing a desktop calculation using the EPA LFG emissions model with prescribed default values (Tier 1),
- determining NMOC emissions using EPA Test Method 25C (Tier 2), and
- performing a pump test program to estimate the generation rate (k) for use in the model using EPA method 2E (Tier 3).

If landfill emissions exceed 150 Mg/year, the facility can opt to install controls after each tier or can proceed to the next tier testing requirements. Recalculation of emission rates for facilities which are exempt from controls must be performed at intervals specified in the regulations.

The proposed standards for new landfills are that the best demonstrated technology (BDT) will reduce emissions from new landfills emitting 150 Mg/yr of NMOC or more with:

- a well-designed and well-operated gas collection system, and
- a control device capable of reducing NMOC in the collected gas by 98 weight-percent.

The proposed guidelines for existing landfills are that BDT will reduce emissions of existing landfills emitting 150 Mg/yr of NMOC or more with the same collection and control devices as required for new landfills. A collection system would:

- handle the maximum gas generation rate,
- incorporate a design capable of monitoring and adjusting the operation of the system,
- collect gas effectively from all areas of the landfill that warrant control, and
- expand by the addition of further collection system components to collect gas from new areas of the landfill as they require control.

The control device is an open flare capable of reducing NMOC emissions by 98 weight-percent. The proposed standards and guidelines also specify additional monitoring and reporting requirements.

After promulgation of the NSPS for municipal landfills, compliance with the guidelines for collection and control systems is required within 3 years from the time of promulgation of state regulations. The 3-year time period allows 90 days for the initial report; 2½ years for further site specific testing (if elected by the owner or operator); preparation and review of a collection system design plan; installation of the collection and control system; and 90 days for a performance test. Landfills that may already have collection and control systems in place may not require the 3 years to bring their systems in to compliance.

To comply with NSPS for municipal landfills, the design and construction of new landfills which meet the applicability criteria must include the gas collection and control requirements defined in the rules. Facilities should evaluate the potential for including energy recovery in the design of new LFG control systems.

5.3.2 NESHAPs

The NESHAPs, promulgated under the Federal CAA (40 CFR Part 61 and 63) may potentially affect LFG operations at industrial sites although NESHAPs have not yet been proposed for LFG operations or solid waste landfills. NESHAPS have been established for benzene, vinyl chloride, asbestos, beryllium, coke oven emissions, inorganic arsenic, mercury and radionuclides. Of these, only asbestos currently has a section in its NESHAPS dealing with waste disposal. In the future, new NESHAPS may be promulgated which could affect other materials accepted by landfills.

5.3.3 Title III

Title III of the CAAA completely overhauled the existing hazardous air emission program. Title III includes a listing of Hazardous Air Pollutants (HAPs), the development and promulgation of Maximum Achievable Control Technology (MACT) standards, and the assessment of residual risk after the implementation of MACT.

Title III shifts its focus from a pollutant-by-pollutant basis to a service category basis. EPA was required to publish a list of major source categories and subcategories. The December 3, 1993 Federal Register published the Categories of Sources of Hazardous Air Pollutants and Regulation Promulgation Schedule by Industry Group and Source Category. The schedule date for the category of municipal landfills (under the Waste Treatment and Disposal Group) is November 15, 2000.

5.3.4 Title V

5.3.4.1 Title V Overview

EPA intends to use the Title V permits as a central mechanism to handle emissions constraints, monitoring data needs, compliance schedules, fee payments, and other conditions associated with the issuance, compliance and enforcement of operating permits. Title V established procedures and requirements for permitting of several source categories, including sources of hazardous air pollutants.

Regulations pursuant to this Title will require the landfill to consolidate the source's regulatory requirements into a single operating permit. Regulatory requirements relevant to landfill operations that must be included in the Title V permit include:

- Title I Non-attainment Status,
- Title III Air Toxics,
- Title VII Enforcement and Compliance,
- State Permit Programs, and
- Existing SIPs and Federal Implementation Plans (FIP).

5.3.4.2 Title V Applicability

Title V of the CAAA requires states to develop an air permitting program that conforms to requirements of the CAAA. The facility operating permit will be valid for five years. This requirement to prepare an operating permit is triggered by any of the following requirements:

- Emission rates of criteria pollutants of 100 tons per year for attainment areas (Triggers for non-attainment areas are lower and are based on attainment status).

- Emission rates of toxic pollutant of 25 tons per year combined or 10 tons per year of any one toxic compound.

- Facilities subject to NSPS or NESHAPS.

- Facilities subject to Title IV- Acid Rain provisions.

While the NSPS requirements for landfills have not been finalized at this time, it is likely that landfill operations will trigger the NSPS and hence subject the facility to the Title V operating permit program.

5.3.4.3 Title V Schedule

Title V operating permit submission is dependent on the approval by the EPA of state Title V programs and the implementation schedules defined in the state programs. State program proposals were due to the EPA by November 15, 1993 and the EPA must accept or reject the state proposal by November 15, 1994. Facilities will be required to submit their initial Title V Operating Permit Applications within 12 months after EPA's approval of a state permit. States are required to act on at least one-third of these permit applications each during a three year phase. The facility should review the applicable state Title V program to determine specific schedule requirements.

5.3.4.4 Title V Compliance

To comply with Title V regulations, landfill operators must check with their lead agency enforcing the Title V program to understand the compliance requirements and schedule for the program and submit a complete application prior to the specified deadline. In general, to comply with Title V, a landfill owner/operator must:

- Understand the requirements of the state program, including monitoring requirements and emission inventory protocols;

- Review all applicable federal, state and local rules and regulations relevant to landfill operations;

- Review the compliance status of all equipment at the facility;

- Prepare an emissions inventory based on defensible emission factor or source test data; and

- Prepare an application package meeting specific state requirements and utilizing specific state forms.

5.4 SECONDARY AIR EMISSIONS

Control devices used to reduce landfill air emissions can be expected to generate secondary air emissions of NO_x, SO_2, CO, PM, and CO_2. Table A-6 summarizes the secondary air emissions from various control techniques. From the narrow perspective, emissions of PM, SO_2, NO_x, CO, CO_2, and HCl at the landfill site may be increased due to operation of the control device. For landfill energy recovery devices such as gas turbines and internal combustion engines, the energy recovered is expected to reduce local or regional electric utility power generation. Since emissions from combusting LFG are less than combustion of coal at utility generating plants per unit of energy, LFG recovery systems could actually reduce emissions.\

5.5 CWA REGULATIONS

Under the CWA, if LFG condensate is disposed of by treatment and effluent discharge to a waterway, discharge permits will be required and stringent effluent quality may be required to meet a state's water quality standards. Effluent analyses required for all discharge permits includes:

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

Other analyses may be required if other pollutants are expected to be present. Permittees may also be required to test their discharge for toxicity.

Table A-6
Secondary Air Emissions from Control Techniques

Control Technique	Secondary Air Emissions (lb/MM scf LFG)[1]					
	NO_x	CO	HCl	CO_2	PM	SO_2
Enclosed flare	4.9	58	12	60,000	Trace	3.0
Incinerator	4.9	58	12	60,000	Trace	3.0
Boiler	70	17	12	60,000	Trace	3.0
Gas turbine	26.4	12.5	12	60,000	37	3.0
Internal combustion engine	111	259	12	60,000	Trace	3.0

[1]- Reference 3

If the condensate is disposed of by indirect discharge through a POTW, sewer effluent conditions will be imposed by the local POTW as regulated by local ordinances or federal requirements.

5.6 STATE AND LOCAL REGULATIONS

Some states and local authorities have also adopted rules that impact LFG emissions. A comprehensive review of all state rules is outside the scope of the document but typical requirements of state programs include:

- Air toxics and NMOC monitoring,
- Air emissions inventories,
- Risk evaluations,
- LFG collection design requirements, and
- Emissions control design requirements.

As an example of a state program, the California regulatory program for landfills requires emissions testing and quantification, risk assessments, and in some cases risk reduction.

LFG management in non-attainment areas in California is regulated by the New Source Review (NSR) Best Available Control Technology (BACT) rule. BACT specifies control requirements for emissions of non-attainment pollutants for new or modified sources. The South Coast Air Quality Management District and several other air districts in California are subject to a FIP to achieve attainment of the Federal ozone standards. The FIP required landfills to control NMOC based on the proposed NSPS for municipal LFG. The FIP essentially accelerates the implementation of the municipal landfill NSPS for the affected regions.

The California program is comprehensive and exceeds the requirements of most other states at this time. However, design, monitoring, and reporting requirements under RCRA Subtitle D and The CAAA Title III and Title V will bring most states in line with California LFG management standards.

Experience from previous design works by the Corps of Engineers on military landfill-gas-collection system found that few of the federal regulations on air emission control were applied. Either the regulations will not directly apply or the landfill will not emit enough NMOC or air toxics to fall under federal regulations. It is the state in which the landfill is located will regulate the acceptable emissions to the air, hence the landfill emission control requirements, and gas collection control systems. The designer should, therefore, review the state regulations, and work with the state air regulators while designing a landfill gas collection and control system.

Some states provide little guidance to the designers as to what emission control requirements are. In this case, a well designed stack in an area with favorable meteorology will adequately protect public health and will not require control provided a dispersion modeling be conducted to prove protection of public health from point sources of toxic air emissions.

5.7 GLOBAL WARMING AGREEMENT

Effects of LFG which are now being debated include tropospheric ozone formation, stratospheric ozone depletion, air toxics, global climate change and acid rain. Through an international agreement on global warming, the U.S. has committed to stabilizing greenhouse gas emissions to 1990 levels by the year 2000. These emissions lead to the "greenhouse effect" which is caused by the buildup of $C0_2$. $C0_2$ allows light from the sun's rays to heat the earth but also prevents the loss of the heat. Currently, no federal regulations require landfills to reduce greenhouse gases emissions. However, in order to stabilize greenhouse gas emissions to 1990 levels, the U.S. must develop a program to reduce $C0_2$ emissions or to offset these emissions by planting trees. As landfills emit the greenhouse gases CH_4 and $C0_2$, it is anticipated that future regulations may be developed requiring emission reduction by energy recovery. Attempts to control CH_4 by combustion will increase the $C0_2$ emissions. However, combustion of CH_4 to provide energy will displace the corresponding amount of fossil fuel combustion for energy generation. This efficient use of LFG for energy recovery is described in the proposed NSPS for municipal landfills.

6.0 ENVIRONMENTAL ISSUES

This chapter discusses the adverse effects of LFG and the benefits of LFG control.

Environmental issues associated with LFG emissions include human health, the environment, and safety. Solid waste LFG presents a potential hazard to human health and the ecological system if left uncontrolled. LFG can be:

- explosive,
- corrosive,
- odorous,
- toxic, and
- asphyxiating.

Therefore, proper control of LFG is essential to ensure the well being of public health and the environment.

Gases found in landfills include air, ammonia, $C0_2$, carbon monoxide, hydrogen, H_2S_5, CH_4, nitrogen and O_2. In addition, various organic compounds may be present in the gas depending on the types of wastes placed in the landfill. $C0_2$ and CH_4 are the principal gases produced from the anaerobic decomposition of organic solid waste components. The high initial percentage of $C0_2$ is the result of aerobic decomposition. The potential adverse effects which can be caused by LFG emissions are further described in the following paragraphs.

6.1 EFFECTS ON HUMAN HEALTH

LFG can asphyxiate a person in an enclosed area or confined space. Enclosed areas include trenches, vaults, underground storage tanks, or building foundations. A confined space is defined by OSHA as a space that:

- is large enough and so configured that a person can bodily enter and perform work,

- has limited or restricted means for entry or exit, and

- is not designed for continuous human occupancy.

The combustion of LFG can also pose a serious health risk to nearby residents and landfill operating personnel. LFG can migrate into confined spaces and can ignite causing serious property and human health damage.

6.2 TOXICOLOGICAL PROFILES OF LFGs

Typical municipal LFGs include CH_4, $C0_2$, nitrogen, paraffinic hydrocarbons, polycyclic aromatic hydrocarbons, hydrogen, H_2S, CO, benzene, vinyl chloride, toluene, 1,2-dichloroethane, chloroform (trichloromethane), 1,1,1-trichloroethane, carbon tetrachloride, and tetrachloroethene, among others. Combustion of LFGs will result in products such as $C0_2$, water, sulfur compounds, and hydrogen chloride along with trace amounts of gases that may result from incomplete combustion of parent compounds. Toxicological profiles of specific chemicals are summarized in Table A-7.

6.3 EFFECTS ON SOIL/VEGETATION

LFG, for the most part, does not have adverse effect on soil after it has passed through it. The LFG moves through the pore space within the soil, and once the gas has evacuated the pore space, the soil returns to its initial condition.

CH_4 gas generated in landfills kills vegetation. The gas displaces the O_2 from the root zone and thus chokes off the plant.

6.4 ODOR PROBLEMS

Landfill odors emanate from open areas of the site due to the decomposition of solid waste and hence the production of LFG. Typically, the strong odors that emanate from LFG are due to ammonia and sulfide constituents that are in the gas. Contrary to popular belief, CH_4 and CO_2 are both odorless and colorless.

Odors from landfills can have adverse public health impacts. Apart from being unpleasant for nearby residents, odors can attract insects and other vermin, such as rats, pigeons, seagulls and bears.

Table A-7
Toxicological Profiles of Select Landfill Emissions

Chemical	CAS No.[1]	Chemical State	Health Hazard	ACGIH TLV[2]	OSHA PEL[3]	Combustion Products
Ammonia	7664-41-7	Gas (pungent suffocating odor)	Eye, nose, throat irritant, skin burns, pulmonary edema, chest pain, bronchial spasms; corrosive	TWA[4] - 25 ppm STEL[5] - 35 ppm	TWA - 50 ppm	NO_x, H_2O
Benzene	71-43-2	Liquid (sweetish odor)	Group 1 Human Carcinogen; skin irritant and inhalation absorption; short-term exposure results in drowsiness, dizziness, headaches and digestive system irritation.	TWA - 10 ppm	TWA - 1[6] ppm/ 10[7] ppm	H_2O, CO_2; also carbon under non-oxidative conditions
Carbon Dioxide	124-38-9	Gas	Simple Asphyxiant	TWA - 5000 ppm STEL - 30,000 ppm	TWA - 5,000 ppm	Fully oxidized
Carbon Monoxide	630-08-0	Gas	Flammable, inhibition of cell oxidation following inhalation	TWA - 25 ppm	TWA - 50 ppm	CO_2
Carbon Tetrachloride	56-23-5	Liquid (sweet aromatic odor)	Group 2B Possible Human Carcinogen; Short-term inhalation: hemorrhagic congestion, edema of lungs, renal injuries, dyspnea, nausea, vomiting and gastrointestinal pain, swollen and tender liver, jaundice, nephritis and nephrosis, skin rashes and CNS[8] depression	TWA - 5 ppm STEL 10 ppm	TWA - 10 ppm (C)[9] - 25 ppm[7]	CO_2, H_2O, HCl, phosgene
Chloroform	67-66-3	Liquid (Sweet odor)	Group 2B Possible Human Carcinogen; respiratory adsorption; CNS depression, anesthesia, cardiac sensitization; skin irritation	TWA - 10 ppm	(C) - 50 ppm	H_2O, CO_2, HCl, phosgene.
1,2-Dichloroethane (Ethylene dichloride)	107-06-2	Liquid	Group 2B Possible Human Carcinogen; Respiratory tract irritation, circulatory failure, CNS depression, cough, nausea or vomiting, cyanosis, coma; dermatitis, eye irritation.	TWA - 10 ppm	TWA - 50 ppm (C) - 100 ppm[7]	H_2O, CO_2, H_2
Hydrogen	1333-74-0	Gas	Flammable, explosive, simple asphyxiant	No TLV: Concentration of oxygen is limiting factor.	No PEL: Concentration of oxygen is limiting factor.	H_2O
Hydrogen Sulfide	7783-06-4	Gas (odor of rotten eggs)	Flammable, respiratory absorption, inhibition of cellular respiration leading to death, coma, convulsions, apnea, pulmonary edema, irritated eyes, conjunctivitis, dizziness, headaches, cough, insomnia, nausea	TWA - 10 ppm STEL - 15 ppm	TWA - 10 ppm (C) - 20 ppm[7]	H_2O, SO_2, SO_3
Methane	74-82-8	Gas	Flammable, explosive, simple asphyxiant	No TLV: Concentration of oxygen is limiting factor.	No PEL: Concentration of oxygen is limiting factor.	H_2O, CO_2
Nitrogen	7727-37-9	Gas	Simple Asphyxiant	No TLV: Concentration of oxygen is limiting factor.	No PEL: Concentration of oxygen is limiting factor.	Inert

Table A-7
Toxicological Profiles of Select Landfill Emissions

Chemical	CAS No.[1]	Chemical State	Health Hazard	ACGIH TLV[2]	OSHA PEL[3]	Combustion Products
Polycyclic Aromatic Hydrocarbons (as coal tar pitch volatiles)	Class	Solids	Group 1 Human Carcinogens: benzo(a)anthracene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, indeno(1,2,3-cd)pyrene.	TWA - 0.2 mg/m^3 for benzene-soluble fraction of coal tar pitch volatiles (including benzo(a)pyrene)	TWA - 0.2 mg/m^3	H_2O, CO_2; also carbon under non-oxidative conditions.
Toluene	108-88-3	Liquid (sweet odor)	Flammable; absorbed from respiratory and gastrointestinal tract; short-term inhalation lightheadness, euphoria, dizziness, sleepiness, unconsciousness, death; skin irritation and dryness; eye irritation	TWA - 100 ppm	TWA - 200 ppm (C) - 300 ppm[7]	Carbon, CO_2, H_2O
1,1,1-Trichloroethane (Methyl chloroform)	71-55-6	Liquid (ethereal odor)	Short-term inhalation: anesthesia, CNS depression and/or fatal arrhythmias; skin irritation; long term dermal contact: edema, ethythema, inflammation, cellular degeneration	TWA - 350 ppm STEL - 450 ppm	TWA - 350 ppm	H_2O, CO_2, HCl, phosgene
Vinyl Chloride	75-01-4	Gas (sweet odor)	Flammable, peroxide former; Group 1 Human Carcinogen; long term exposure dizziness, nausea, headache, tingling sensations, fatigue, bone swelling, circulatory disorders, CNS system disorders, lung function impairments, immune system dysfunction	TWA - 5 ppm	TWA - 1 ppm STEL - 5 ppm	CO_2, CO, HCl, phosgene

[1] - Chemical Abstracts Registry Service Number.
[2] - American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV), 1991 6th Edition.
[3] - Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PEL), 29 CFR 1910.1000 Table Z-1.
[4] - TWA - Time-weighted average concentration for a normal 8-hour workday and a 40-hour workweek to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.
[5] - STEL - Short-term exposure limit or a 15-minute TWA exposure which should not be exceeded at any time during the workday even if the 8-hour TWA is within the TLV-TWA.
[6] - OSHA 29 CFR 1910.1028
[7] - OSHA 29 CFR 1910.1000 Table Z-2
[8] - Central Nervous System (CNS)
[9] - Ceiling (C)

Odor problems from a landfill mostly occur when a landfill is open (i.e., in operation). Closed landfills should include design provisions for odor containment, whether it be through a gas flaring system or through controls such as carbon filtration units.

6.5 NOISE AND VISIBILITY

The aesthetics of constructing a LFG control system must be incorporated into the final design. Unsightly and/or noisy resource recovery systems, flaring systems, or passive gas venting systems can cause public outcry.

6.6 EXPLOSION AND FIRE POTENTIAL

CH_4 gas is explosive between 5 and 15 percent concentration in air. The uncontrolled release of CH_4 gas can be very dangerous. CH_4 gas has been documented to accumulate in basements of buildings and/or residential homes, and has exploded causing serious injury to people and property.

CH_4 gas entry points into a building may be through cracks, construction joints, subsurface utility service openings, and almost any other weak spot in the basement wall or building floor. CH_4, being lighter than air, will tend to accumulate near the ceiling.

The uncontrolled release of CH_4 in subsurface strata poses a substantial risk of underground fires as well as explosions. Underground fires from CH_4 are common in peat bogs and swamps as well as landfills during arid weather conditions. Proper LFG controls such as passive gas systems can eliminate the potential for underground fires.

7.0 CONSTRUCTION MATERIALS AND INSTALLATION

7.1 GENERAL

This chapter discusses construction materials and installation guide for LFG recovery, treatment, and condensate management systems.

A primary consideration in determining suitable construction materials for LFG systems should be the compatibility of the construction materials with the LFG and condensate.

7.2 CONSTRUCTION MATERIALS

Construction materials discussed in this section include:

- gravel pack,
- cap and liner,
- piping material,
- valves and fittings, and
- blower and flare.
- LFG condensate

Combustion engines using LFG for energy recovery and the purification techniques to upgrade LFG to pipe line gas will not be discussed in this ETL as they are not likely applicable to the small landfills at most military installations.

7.2.1 Gravel Packs and Trenches

As discussed in previous sections, gas extraction wells, and collection trenches utilize gravel as the primary conveyance or as a pack around perforated collection pipes. Selection of the gravel material should be based on gas conductivity, grain size and pH.

A significant part of the system design should include the evaluation of the potential for granular materials to "sift" down into the waste pack. Where a high potential for the loss of granular material into the waste pack exists, a separation geotextile should be used.

Most clean, free-draining sands and gravels placed in a relatively dry condition function adequately for gas collection and conveyance purposes. As a general "rule-of-thumb," those soils which function best for LFG systems contain less than 6 percent by weight (74 microns or 0.0029 inches) passing the No. 200 sieve (U.S. Standard) and have a hydraulic conductivity coefficient (k) of greater than 10^{-3} cm/s. Soils which contain higher fractions of fines may function adequately during the initial phases of the operation, but experience has shown that these soils are more susceptible to clogging as a result of biological activity and saturation from the leachate.

Gravel packs installed with particle sizes which are too small tend to "sift" into the waste leaving either a void. Those with grain size distributions which are too large tend to entrain and accumulate fine particulate matter which can either clog the gravel pack or the filter fabric around the header.

Typically, gravel packs for wells and trenches have been sized using the procedures in the EPA's Manual of Water Well Construction Practices (EPA - 570/9-75-001), and USACE EM 1110-1-4001 Soil Vapor Extraction.

Although most sands and gravels are relatively inert in leachate and LFG condensate, some specific construction materials which pose potential compatibility problems should be avoided. For example, crushed limestone should not be used in LFG extraction wells or collection trenches systems due to LFG low pH conditions which may dissolve the lime stone.

7.2.2 Cap and Liner Systems

Historically, landfill caps and liners have been used principally to control the migration of leachate from the landfill. These cap and liners have typically consisted of natural geologic formations, compacted clay, geomembranes, and geosynthetic clays liners.

The purpose of the clay barrier layer in a composite cover (clay-geomembrane) is to inhibit the movement of gases and water which passes through holes in geomembrane. Soils used for clay barrier layer are selected to meet a specific conductivity requirement (typically 1 x10^{-7} cm/sec). If a clay liner is to be used for gas migration control, the designer should evaluate:

- clay permeabilities
- clay shrink-swell behavior
- water contents and saturation limits at the specified compaction densities
- operational schemes to determine the potential for desiccation drying

Geosynthetic clay liners (GCLs) are used to augment or replace compacted clay layers or geomembranes. GCLs are factory manufactured hydraulic barrier consisting of bentonite clay materials supported by geotextiles or geomembranes. GCLs are available in widths of 2.2 to 5.2 m (7 to 17 ft) and lengths of 30 to 60 m (100 to 200 ft).

Geomembrane liners are synthetic films placed along the bottoms, sides and caps of landfills to control leachate and gas migration. Typical liner materials consist of high density polyethylene (HDPE), very low density polyethylene (VLDPE), chlorinated polyethylene (CPE), chlorosulphanated polyethylene (Hypalon), polyvinyl chloride (PVC) butyl rubber and ethylene propylene rubber (EPDM). The thicknesses of these materials range from 20 to 120 mils, depending upon the application.

The most common types of geomembranes currently being used for landfill covers are PVC and very low density polyethylene (VLDPE). High density polyethylene (HDPE) is generally not used for landfill covers because it is less flexible than VLDPE making it more difficult to install and more susceptible to damage by differential settlement.

Detailed design procedures for cap and liner systems are provided in the EPA/625/4-89/022 "Requirements for Hazardous Waste Landfill Design, Construction and Closure", and EPA/625/4-91/0254 "Design and Construction of RCRA/CERCLA Final Covers." The Corps of Engineer Military Guide Specification 02271 "Geomembrane Barrier for Landfill Cover" should be used in contract documents when specifying geomembrane.

7.2.3 Piping and Header Materials

Two types of materials which have principally been used for gas transmission systems are steel and plastic. Because of its inferior corrosion resistance compared to plastic pipe, steel pipe is not recommended for use in LFG collection and conveyance Systems.

7.2.3.1 Plastic Piping

Plastic piping materials can be divided into two basic groups; thermoplastic plastics and thermosetting plastics (see Sections 7.2.3.2 and 7.2.3.3, respectively). When selecting the material to use, a number of factors should be considered. These include:

- durability;
- pipe strength; and
- dimensional stability.

Durability. The service life of a pipe material will depend on the durability of the material and the conditions under which it is exposed during service. The durability of a plastic depends on the polymer, the auxiliary compounding ingredients, the manufacturer and the installation of the product and it can vary greatly with respect to exposure conditions. The deterioration of plastics can take the form of:

- Softening and loss of physical properties due to polymer degradation by depolymerization;

- Stiffening or embrittlement due to loss of plasticizers resulting from repeated usage;

- Deterioration of mechanical properties due to swelling; and

- Failure of adhesive or heat fused joints due to interaction with condensate or leachate and physical stress.

These degradation modes are typically the result of repeated or prolonged physical stress, UV degradation, and chemical attack. Extensive research has been done on the chemical resistance of plastic pipe materials and numerous charts are available that give the relative resistance of a material to a specific chemical. Not as clearly understood, however, is the resistance of plastic materials to the mixtures of chemicals that may occur in the landfill environment. Research done by the EPA on plastic materials used for linings has shown that a wide variety of changes in physical properties can occur after exposure simulating service conditions. Among these are large weight gains (swelling) and loss of strength. The EPA Test Method 9090 may be used to estimate the degradation of specific pipe materials when exposed to site specific condensates.

Strength. Strength considerations for both PE and PVC (thermoplastic) pipes have been extensively researched and are well documented in manufacturers literature. Published strength characteristics are specified at certain temperatures. Actual service temperatures must be considered in designing the pipe system so that changes in strength characteristics due to elevated temperatures are considered in the material selected.

Property Changes. Changes in the physical properties of plastic pipe can be caused by various kinds of exposure to the outdoor environment. Weather effects can be minimized or eliminated by the proper storage and installation of the pipe. Materials not protected from UV radiation with the addition of carbon black should be protected both during storage and in service to prevent degradation.

All materials change dimension as a result of temperature changes. PE and PVC differ greatly in their respective changes in size as temperature changes. PVC has a thermal expansion coefficient of $3x10^{-5}$ in/in per ^{0}F of temperature change. PE pipe is three times higher or $9x10^{-5}$ in/in per °F. In a buried environment, where the temperature fluctuations should be minimal and the pipe is supported on all sides by soil, thermal expansion is of less concern. However, in systems where the collector pipes are above ground, thermal expansion and contraction must be considered in the design.

7.2.3.2 Thermoplastic Materials

Types of thermoplastic pipes include acrylonitrile-butadiene-styrene (ABS), cellulose acetate butyrate (CAB), polybutylene (PB), polyethylene (PE), and polyvinyl chloride (PVC).

ABS and CAB are materials that were used in natural gas transmission during the 1940s but are very rarely used today. PB has not found much acceptance for use because of inferior physical performance as compared to PE or PVC. PVC and PE are the most common types of thermoplastic pipe materials used. A survey conducted by the Governmental Refuse Composting and Disposal Association (GRCDA), now named Solid Waste Association of North America (SWANA), about LFG collection systems found that PVC and PE accounted for 97.7 percent (72.7 percent PVC, 25 percent PE) of the material used in the horizontal collector pipes and 95.4 percent (88.6 percent PVC, 6.8 percent PE) of the materials used in the vertical well pipes. PVC and PE are discussed further below.

PVC. PVC is produced by refining petroleum into naphtha, then to ethylene. Ethylene and chlorine are then combined to form vinyl chloride which reacts with a catalyst to form PVC. The PVC resin (or powder) is then mixed with a variety of additives to form the desired specific formulation of PVC required. The additives can include pigments, lubricants, stabilizers, and modifiers. The amount and types of these additives have a significant effect on the final PVC product. PVC formulations used for piping purposes contain no plasticizers and little of the other ingredients mentioned. These are known as rigid PVCs and are differentiated from the plasticized, or flexible PVCs such as those used to make upholstery or luggage.

PVC pipe sizes may be specified by schedule class or Standard Dimension Ratio (SDR). The SDR is the ratio of the pipe diameter to the wall thickness. Schedule 40 is a thin-wall pipe and cannot be threaded. Schedule 80 PVC pipe may be threaded and is used for more severe applications at higher working pressures. Standards for PVC pipe are given in ASTM D1785 for Schedules 40, 80 and 120.

PVC in general can be joined by adhesives, heat, or mechanical methods. Rigid PVC pipe is usually joined by epoxy adhesives. There are specific types of adhesives recommended for use with both Schedule 40 and 80 pipe and one must be careful to use the appropriate type. Standard specifications for PVC pipe can be found in ASTM D2564. In addition, because PVC is degraded by sunlight, above ground collection piping should, therefore, specify UV resistant material.

Polyethylene (PE): PE pipe is made from High Density Polyethylene (HDPE). HDPE is a thermoplastic material polymerized from ethylene at controlled temperatures and low pressures.

HDPE materials are generally divided into two density ranges: 0.941 through 0.959 and 0.960 through 0.963. The types of PE pipe used in the LFG industry fall into the lower density category. This lower density results in an improvement in impact resistance, environmental stress crack resistance, and flexibility.

PE pipe is classified according to ASTM D 2513, which employs a four digit material designation code. This specification defines the polyethylene pipe types most familiar to those in the LFG industry - e.g. PE 3408. Because of the wide variety of polyethylene pipe materials used today, an additional ASTM standard (D 3350) was developed to augment ASTM D 2513.

PE pipe must be joined by heat methods. Pipe segments and fittings are fused to one another at temperatures of approximately 230^{0}C (450^{0}F). Different thicknesses and types of pipe require different temperatures. There is no known suitable adhesive for polyethylene.

7.2.3.3 Thermosetting Plastics

Pipe used in LFG collection in this category is known as fiberglass reinforced plastic (FRP) orreinforced epoxy resin pipe. The pipe is generally translucent, with fibers imbedded in an epoxy matrix. The exterior has a more uneven finish than either PE or PVC pipe, but the interior is very smooth. The reinforcement in this pipe consists of continuous strands of glass. The direction and density of the glass affect the physical strength properties of the pipe. FRP pipe is typically joined by epoxy adhesives or mechanical connections. Threaded joining systems are also available. The use of this type of pipe in LFG collection systems has been limited due to the cost of the materials. It has, however, been used in both vertical wells and horizontal collector pipes.

The advantages of using FRP pipe in LFG collection include:

- high strength and durability;
- better resistance for melting at high temperature;
- corrosion resistant; and
- do not fail at low temperature.

The disadvantage of this material is high cost.

7.2.4 Valves, Fittings, Etc.

Valves used in the LFG control management include: globe valves, butterfly valves, gate valves, check valves, sample valves (labcock) and relief valves. The following considerations should be given when selecting valves:

- The type of service required. For example, globe valves can more accurately "pinch" or control a flow rate in gas or multi-phase service than butterfly valves; butterfly valves can more accurately control a flow rate in gas or multi-phase service than gate valves.

- Gate valves are used only to open or close the flow;

- Check valves are used to allow flow in one direction only;

- The corrosive properties of the gas. (discussed in the previous section.)

- The likely temperature conditions at an exposed site. PVC valves are prone to failure at low temperatures, therefore, lined metal or HDPE valves are preferable for cold-weather service.

- The strength and durability of the internal components. 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.

The selection and layout of valves in the LFG system should be carefully evaluated during the project's review process to ensure that the level of control provided in the systems is consistent with projected 0&M needs. A summary of valve applications on a typical active LFG collection system is presented in Table A-8.

7.2.5 Conduit Seals

Conduit seals are very important to prevent the migration of LFG through the electric conduit system. Where fugitive emissions or project cleanliness is a concern, gaskets or seals may be required on fittings, flanges and valves. Conduit seals should be located on underground conduits between the ground surface and panels or equipment where sparking components are located.

A wide variety of sealing materials is available; each with its own advantages and disadvantages. These sealing materials should be carefully evaluated for the specific application. Industrial plastics are the primary class of materials used for LFG applications. Table A-9 summarizes a comparison of various plastics and elastomers used for pipeline, fittings, valves, and seals as prepared by Fisher (1989). For additional information on these products, refer to the Industrial Plastic Systems Engineering Handbook by George Fisher (1989).

TABLE A-8

Summary of Plastic Materials Used for LFG Applications

Material	Abrv.	General Chemical Resistance	Maximum Permissible Water Temperature °C	
			Constant	**Short Term**
Polyvinyl Chloride	PVC	Resistant to most solutions of acids, alkalis and salts and to organic compounds miscible with water. Not resistant to aromatic and chlorinated hydrocarbons.	60	60
Chlorinated Polyvinyl Chloride	CPVC	Similar to PVC but at temperatures up to 90°C.	90	110
High Density Polyethylene	HDPE	Resistant to most solutions of acids, alkalis and salts many organic solvents. Unsuitable for concentrated oxidizing acids.	60	80
Polypropylene, heat stabilized	PP	Similar to HDPE but suitable for higher temperatures.	90	110
Polyvinylidene Fluoride	PVDF SYGEF ®	Resistant to acids, solutions of salts, aliphatic, aromatic and chlorinated hydro-carbons, alcohols and halogens. Conditionally suitable for ketones, esters, ethers, organic bases and alkaline solutions.	140	150
Polybutylene-1	PB	Similar to HDPE but for higher temperatures.	90	100
Polyoxymethylene	POM	Resistant to most solvents and hydrous alkalis. Unsuitable for acids.	60	80
Polytetrafluoroethylene (e.g. Teflon®)	PTFE	Resistant to most chemicals	250	300
Nitrile Rubber	NBR	Good resistance to oil and petrol. Unsuitable for oxidizing media.	90	120
Butyl Rubber Ethylene Propylene Rubber	BR EPDM	Good resistance to ozone and weather. Suitable for many aggressive chemicals. Unsuitable for oils and fats.	90	120
Chloropene Rubber (e.g. Neoprene®)	CR	Chemical resistance similar to PVC and between that of Nitrile and Butyl Rubber.	80	110
Fluorine Rubber (e.g. Viton®)	FPM	Has best chemical resistance to solvents of all elastomers.	150	200
Chlorine Sulfonyl Polyethylene (e.g. Hypalon®)	CSM	Chemical resistance similar to that of EPDM.	100	140
Perfluoro (ethylene-propylene) copolymer	FEP	Resistant to most chemicals, some strong acids will oxidize at high temp. and pressure.	205	220
Perfluoroalkoxy	PFA	Similar to FEP but with higher temperatures.	260	280
Ethylene/Chlorotrifluoroethylene copolymer	ETCFE Halar®	Good resistance to stress cracking in contact with alkaline and chlorine	180	200

TABLE A-9

Summary of Valve Applications

Valve Types	Applications	Advantages/ Disadvantages	Construction Materials
Gate valves	Duty: Stopping and starting flow. Infrequent operation Service: Gases/Liquids Vacuum/Cryogenic	Used only when the pressure drop through the valve is minimal	Carbon steel Ductile iron Cast iron PVC Plastic Austenitic Stainless Steel
Plug Valves	Duty: Stopping and starting flow. Moderate throttling. Flow diversion Service: Gases/Liquids/Vacuum Non-abrasive slurries Abrasive slurries used lubricated plug valve.	Minimum of space Simple operation Ease of actuation and tight shutoff	Carbon steel Ductile iron Cast iron Bronze PVC Plastic Austenitic Stainless Steel
Ball Valves	Duty: Stopping and starting flow. Moderate throttling. Flow diversion Service: Gases/Liquids. Vacuum/Cryogenic Non-abrasive slurries Most effective when fully open or closed.	Offer quick operation that is self sealing, and tight shutoff	Carbon steel Ductile iron Cast iron Bronze PVC Plastic Austenitic Stainless Steel
Globe Valves	Duty: Used to control (throttle) flow. Stopping and starting flow. Frequent valve operation. Service: Gas/Liquids essential free of solids. Vacuum/Cryogenic	Resistance increases when the direction of fluid flow through these valves changes	Carbon steel Ductile iron Cast iron PVC Plastic Austenitic Stainless Steel

TABLE A-9

Summary of Valve Applications

Valve Types	Applications	Advantages/ Disadvantages	Construction Materials
Check Valves	Duty: Open with forward flow Close against reverse flow. Service: Generally used with gate valves because of similar flow characteristics. Is required in a secondary system in which the pressure can rise above that of the primary system.	Offer quick automatic reactions to flow changes. Swing check valves offer minimum resistance to flow	Carbon steel Ductile iron Cast iron PVC Plastic Austenitic Stainless Steel
Butterfly Valves	Duty: Used to control (throttle) flow. Stopping and starting flow. Service: Gases/Liquids/Vacuum. Powder/Granules/Slurries Used for larger throttling valves	Initial low cost. Ease of installation and actuation.	Carbon steel Ductile iron Cast iron, PVC plastic Plastomeric materials for high temperature and corrosion resistance.
Three-Way Valves	Duty: Used to change flow direction Stopping and starting flow. Service: Gases/Liquids/Vacuum. Used on condensate tank to drain or to release vacuum.	Offer quick reactions to flow changes and tight shutoff. Ease of installation	Carbon steel Ductile iron Cast iron, PVC plastic Plastomeric materials for high temperature and corrosion resistance.
Sample Valves	Duty: Stopping and starting flow. Service: Used to take samples on a pipe/tank or on a gas well Gases/Liquids Pressure/Vacuum	Initial low cost Ease of installation	Carbon steel Ductile iron PVC Bronze Plastomeric materials for high temperature and corrosion resistance.

Source: Adapted from "Valve Selection Handbook, 2nd Edition", R.W. Zappe

7.2.6 Blowers

Section 4.4.3.2 discusses types and applications of blowers for LFG management. This chapter discusses the construction material of the blowers applied to LFG service.

Since LFG may contain particulates and aqueous vapor such as H_2S which is corrosive, a protective coating should be applied to all blower parts in contact with the LFG.

Experience with centrifugal blowers utilized in LFG collection has shown that cast aluminum impellers coated with a baked phenolic coating have been used with success against the corrosion effects of H_2S and of most other chemicals(22). Stainless steel impellers without coating can be used, but the cost is very high.

Non-sparking impellers are recommended in centrifugal blowers to prevent gas ignition problems within the blower should an impeller contact the casing as the result of a bearing failure.

Ball bearings should be made with friction-resistant material, and designed to Antifriction Bearing Manufacturing Association AFBMA 9 and AFBMA 11 standards for a calculated life expectancy of 200,000 hours.

To absorb vibration during operation, flexible connections should be provided on both inlet and outlet sides of the blower. Since the LFG may be explosive, the blower motor should be explosion-proof and suitable for Class I, Division I, Group D, Hazardous Locations. Motor Code is discussed in Section 4.

7.2.7 Flare

The following materials can be specified for flare components:

Burner:

- 304L or 316L stainless steel;
- special nickel alloys, such as monel, inconel, hastelloy;
- venturi liners should be castable refractory, and

- should have temperature rating at 2700°F.

Flare Stack:

- shell material is made of 3/8"thick ASTM A36 carbon steel with exterior and interior coatings for corrosion resistance;
- ceramic fiber for insulation materials; and
- The allowable radiation to meet specific needs (unattended station or location where personnel may need to perform work for a short period of time);

Flare Tip:

- flare tip (upper section of the flare) should be made of high temperature stainless steel (304L or 316L) materials.
- the tip size to meet the velocity requirements of Federal Regulations 40CFR 60.18.

Flame Arrestor:

- arrestor element can be aluminum or 316 Stainless steel;
- element housing can be welded steel or 316 Stainless steel.

In general, the selection of construction materials for flares is based on the size, service life, and material and fabrication cost. Manufacturer consultation is recommended for selection of construction materials for flares because the cost of materials, fabrication, and machining as well as service life may vary significantly.

7.2.8 LFG Condensate

An important design consideration for LFG condensate treatment systems is to prevent condensate as much as possible. Because LFG condensate is very corrosive, avoid to use carbon steel where aqueous phases may occur. HDPE and FRP are suitable materials for condensate collection at atmospheric pressure. When carbon steel components are required in services with the potential for exposure to low pressures (less than 70 KPa), exposed steel parts should be coated with corrosion resistant plastics. Exposed steel parts subjected to higher pressures should be coated with zinc or corrosion resistant epoxies.

7.2.8.1 Combustion Engines

Experience has proven that combustion engine parts most frequently susceptible to corrosion or wear are exhaust valves, valve guides and stems. The service life of these components can be notably increased by chrome plating or other surface hardening.

Turbine manufacturers strongly recommended that fuel gas compressor oil and condensate carryover be prevented from entering the engine and combustion system.

7.3 INSTALLATION CONSIDERATIONS

Installation considerations will include the following:

- Gas Well/Trench installation;
- Header Pipe Installation;
- Condensate tank and pumps installation;
- Blower installation; and
- Flares installation.

7.3.1 Gas Wells and Trenches

Wells:

Wells are connected to a collection system that carries the gas to the treatment or energy recovery system. The wells must be individually valved so the vacuum applied to each well can be regulated. Pipe diameters will be determined by the gas flow rate and the need to minimize pressure losses. In addition to requirements described in the previous Section 4.4.2, the regulated. Pipe diameters will be determined by the gas flow rate and the need to minimize pressure losses. In addition to requirements described in the previous Section 4.4.2, the following standards should be used for installation of LFG extraction wells:

- ASTM D5092 - Practice for Design and Installation of Groundwater Monitoring Wells in Aquifer,
- AWWA AlOO - Water Wells,
- USEPA 570/9-75/001 - Manual of Water Well Construction Practices.
- ASTM D F80 - Thermoplastic well casing pipe/couplings made in standard dimension ratios (SDR) schedule 40/80, specification,

<u>Trenches</u>:

The following requirements should be considered for trench installation:

- Correct depth and width of the trench;
- slope of the trench (minimum 2 percent);
- distance between trench (vertical and horizontal),
- gravel-pack base installation;
- liner cover material;
- compaction method;
- pipe joints (following pipe manufacturer's recommendations), and
- cap seal (following geomembrane manufacturer's recommendations).

Some of these requirements are described in the previous Section 4.4.1.2, Trench Collection Systems.

7.3.2 Header Pipes

The following considerations should be used for the installation of LFG-header collection system. Some of these requirements are described in the previous Section 4.4.3.1.

Header Underground:

- excavation elevation, slope,
- gravel bedding placement,
- location and size of header pipe,
- pipe slope to have a minimum 2 percent,
- condensate traps should be at lowest point
- placement of magnetic detection tape to locate pipe by metal detector,
- placement of screened gravel in excavation,

Header Aboveground:

- pipe location;
- pipe slope (minimum 2 percent);
- condensate traps location (at lowest point)
- provisions for thermal expansion/contraction;
- pipe support;
- seal joint or seal connection repair, and
- pipe insulation to keep LFG temperature above dew point.

It is usually preferable to lay the pipe work below ground; above-ground pipes, which require protection from the ultraviolet rays of sunlight, are typically used only on a temporary basis while settlement is taking place. Pipe joints should be minimized. The joints should be sound, with positive seals, and flexible enough to compensate for movement caused by settlement and temperature variations.

7.3.3 Condensate Management

Followings are considerations for the installation of condensate collection system:

- condensate tank location;
- excavation depth, if below grade;
- gravel bed placement for the condensate tank foundation;
- pipe and fitting connections;
- condensate pump installation; and
- Condensate treatment, if required.

Because of the potential for "slugs" of condensate to form in the collection network, valves, fittings, elbows, and control devices should be securely anchored to avoid damage from the water-hammer effects which can result as these "slugs" of water are drawn through the system.

7.3.4 Blower

Followings are considerations for the blower installation:

- blower location;
- foundation plan meeting blower design loads;
- pipe connection;
- noise deflector, if required;
- flame arrestor location; and
- Electrical and control system installation.

The blower should be installed in a shed at an elevation slightly higher than the end of the header pipe to facilitate condensate dripping. For blower motors with horsepowers of 5 or more, a three-phase electrical connection is usually required.

7.3.5 Flare and Appurtenance Installation

In addition to the requirements described in the previous Section 4.4.4.1, the following design parameters should be considered for the flare and appurtenance installation:

- flare location,
- foundations plans meeting design loads,
- fuel-assisted equipment location,
- ladder and safety cage installation,
- location of water seal,
- location of flame arrestor, and installation of temperature controller.

8.0 OPERATING CONDITIONS

8.1 GENERAL

This section describes the various operating conditions including start-up, operation, maintenance requirements and safety issues of an LFG management system such as a flare/blower station. LFG treatment systems, if incorporated, usually involve more complex operation schemes. The operation and control for those systems are site-specific and will not covered in this ETL because of limited use in military installations.

Typically, start-up and the first year of operation and maintenance (O&M) of an LFG control system for military landfills are performed by the contractor. The start-up procedures, however, are described here for reader information.

In general, a start-up plan (or procedure) should be prepared for the entire LFG control system. The start-up plan should take into account the system's design objectives and complexity and will encompass:

- prestart-up checkout,
- prestart-up testing, and
- the actual start-up.

The prestart-up is just a reinspection prior to prestart-up testing because during construction, each component has been inspected for proper installation by a field inspector using a construction check-list. The purpose of the prestart-up checkout is to verify that the components of the system are properly installed according to plans and drawings. The system's Piping and Instrumentation Diagram (P&ID) and the As-Built Drawings are the best documents to use to verify that all equipment, piping, and valves are installed. The electrical One-Line Diagrams and Wiring Diagrams are useful to verify electrical and instrumentation systems. Grounding of equipment should also be checked. Vendor's certified shop drawings and operating manuals for equipments are important documents to check the equipment installation and operation.

The pre-startup testing is designed to verify integrity of the system prior to actual operation. Components subjected to the prestart-up testing may include:

- piping and ducts should be tested for pressure or vacuum to the design requirements;
- blower, condensate pumps should be tested for operability;
- electrical wiring, and lighting should be tested for continuity and/or damage;
- analog control, if installed, are tested with simulated signal to verify operating ranges; and
- valves are checked for position and operability;
- flare fuel-assisted equipment should be tested for operability, and
- Where on-line gas and liquid sampling instruments are being used, calibrate the instruments after all other system components have been tested.

The actual start-up can begin once the prestart-up testing is complete. The start-up should proceed slowly following a start-up plan prepared well in advance. This is extremely important because LFG is toxic and flammable. Pieces of equipment that can be operated without process liquid or vapor should be started first. All equipment to be on "Stand-by" during full operation should be started before process equipment is started. Once steady-state operation is achieved, operation activities will continue to assure smooth operation.

The maintenance is comprised of a series of activities carried out to ensure that equipment, systems and facilities are able to perform as intended and/or to provide consistent performance of the treatment equipment.

The following sections describe start-up operations of an LFG collection and control using a flare-blower station. The start-up procedure proceeds following a planned sequence of events on each component of the collection system.

8.2 WELLS

8.2.1 Prestart-up Checkout.

Prior to initiating start-up of the gas wells, each gas well will be reinspected for completion by the engineer against the checklist completed during the construction and quality control. All wells will be inspected against construction drawings to verify that there are no outstanding construction issues.

8.2.2 Prestart-up Testing

Pretesting may include pressure or vacuum tests and/or valve rating tests. The prestart-up testing on the wells can be omitted if it has been checked and tested by the field inspector during construction and there are no modification or off-specification materials used in the construction.

8.2.3 Start-up

During start-up, each wellhead valve will be fully open. It is possible to optimize the composition of the recovered gas (percent methane) by making adjustments based on the chemical analyses of the landfill gas at different well heads. Observation, sampling and pressure and flow rate measurements at the wellhead will be compared to design parameters to ensure that the system is operating as expected.

Once the system is running at or close to the expected set points, the entire system should be checked. Monitoring data includes the flow, the pressure, and the temperature at each extraction well and at all test points in the system. The operating data are then compared to equipment performance for discrepancies.

At least two sets of measurements should be taken at each well for the first 3 to 4 days of start-up to adjust the valves to maintain the desired percent CH_4 and/or O_2 at the wellhead. After 3 to 4 days, the observations and necessary adjustments will be reduced to one observation per day for the next 10 to 14 days. Following this first 2-week adjustment period, observations should be made every other day for an additional 2 weeks.

As discussed in the previous chapters, military solid waste landfills usually do not produce a high percent CH_4 as do MSW landfills, therefore adjustment of valves for steady-state operation should be based on chemical analyses of the system, i.e., oxygen content in the LFG. An oxygen content less than five percent should be maintained at the well head to prevent underground fire and or explosion.

Monitoring of pressure and flow rate on multiple wellheads will require one internal and one perimeter well to be selected from each landfill area for monitoring. Flow rate will be measured at the flow meter installed on the wellhead. The monitors should be spaced at distances from each wellhead measuring 25, 100 and 200 feet from the well selected for testing. Monitoring frequencies specified above for the gas wells apply also to these monitoring locations.

Information that will be collected includes:

- gas flow rates;
- applied vacuum;
- barometric pressure;
- temperature; and
- baseline chemical quality parameters CH_4, CO_2 and O_2

All data collected and conditions observed will be noted in a log so that future monitoring activities can be referenced to these baseline conditions. Additional monitoring recommendations and sampling methodologies are provided in the LFG Collection System Monitoring Plan as described in Section 4.7.

8.3 COLLECTION LATERAL

8.3.1 Prestart-up Checkout

The laterals will be inspected by the field engineer to ensure all isolation valves and monitoring station valves are fully open. All vacuum gauges installed at various locations on the wells and manifold network are checked for proper operation and set points.

8.3.2 Prestart-up Testing

Safety shut down conditions will be tested manually to inspect the proper operation of safety shut down sequences. These conditions will apply principally to the blower and flare unit systems.

8.3.3 Start-up

Pressure. and flow rate measurements will be obtained at each collection lateral monitoring station and be compared to design parameters. Monitoring frequencies for the collection lateral should coincide with that of the gas wells.

8.4 CONDENSATE COLLECTION SYSTEM

8.4.1 Prestart-up Checkout

Before start-up of the condensate collection system, each of the remote sumps will be inspected to ensure that the pump is properly installed. High liquid level alarms as well as pump on/off level controls should be checked for proper installation. The central knock-out pot will be inspected to ensure that the tank and pumps are in satisfactory condition and that the discharge valves are positioned to permit free drainage of condensate to the condensate storage tank.

8.4.2 Prestart-up Testing

The pumps in the remote sumps as well as the condensate storage tank will operate on levels with operating ranges as projected on the construction drawings. Actual pump cycle times will be dependent on the rate of condensate collection which may not meet design predictions. These pumps can be inspected for operation using tap water. Should condensate levels build-up to unacceptable levels in the tank (i.e., 80 percent), condensate must be removed and hauled to a disposal facility. Safety shutdown conditions will be initiated manually and proper operation of safety shutdown sequences will be inspected.

8.4.3 Start-up

Start-up of the condensate collection system begins after all components of this system have been tested and certified for operation. Once steady-state operation is achieved, operational efficiency data will be collected at each sump. Information that will be collected includes:

- condensate generation rates, and
- pump cycles.

Conditions will be noted in a log so that future monitoring activities can be referenced to these baseline conditions.

8.5 BLOWER

The following activities relate to all three-phases of the start-up for the blower.

8.5.1 Prestart-up Checkout

Prestart-up checkout of the blower is performed by the field engineer to ensure that the unit is properly installed. Control devices such as a clock that record cumulative hours of run-time, an odometer that records the number of cycles should be checked for proper setting. The blower should also be checked for proper oil level and ready for start-up.

8.5.2 Prestart-up Testing

Safety shut down conditions will be initiated manually to inspect proper operation of safety shut down sequences. Noise level will be measured to check compliance with OSHA regulation (85 dB at 5 feet).

8.5.3 Start-up

During start-up, the pressure controls on the blower will be adjusted for minimum vacuum to identify any defects in the blower assembly. The vacuum pressure will be slowly increased to permit the system to stabilize incrementally. Incremental increase in pressure permits periodic inspection of the gas wells and collection lateral system. Following incremental increase to full operating conditions, the gas well balancing activities will be initiated.

During start-up, blower amperage should be monitored to determine the load placed on the blower. Excessive amperage may indicate low flow and/or high vacuums across the blower, which could lead to overheating. Excessive amperage may also indicate that the blower is undersized. Operating conditions such as the flow rate, operating pressure and pressure drops should be noted on a log for future monitoring activities. Additional monitoring needs are discussed in the LFG Collection System Monitoring Plan, Section 4.7.

8.6 FLARE AND APPURTENANCE

8.6.1 Prestart-up Checkout

Prestart-up checkout of the flare is performed by the field engineer to ensure that the unit is properly installed. In addition, flare appurtenances such as the flame arrestor, the flame detector, the fuel-assisted device, and the water seal tank should be verified for proper installation. The flame arrestor seals should be checked on both ends. The temperature control devices on the flare should be checked for proper setting.

8.6.2 Prestart-up Testing

The flame detector safety shut down conditions of the inlet valve due to flare temperature will be initiated manually to inspect proper operation of safety shut down sequences. The pilot light will also tested for operability.

8.6.3 Start-Up

Start-up procedures for control devices should follow those prescribed by the manufacturer. Pressure drop across the flame arrestor shall be measured to ensure compliance with design level (AP < 3').

Once steady-state operation is achieved, condensate aspiration will commence and plans will be made for implementing the flare compliance test as described in the specification.

8.7 MODE OF OPERATIONS

8.7.1 Manual Operation

An landfill off-gas collection and control systems designed for manual operation will employ the least complex degree of automation while maximizing operator interface. Controls will be limited to local monitoring of system pressures, temperatures, flow and gas composition. Valves used to throttle flow and balance the collection system will be equipped with manual operators. Condensate collection and control systems can employ manual drainage devices.

Generally, designs incorporating manual operation would be limited to collection and control of the off-gas. The LFG off-gas treatment systems, if incorporated, usually involve more complex control schemes.

8.7.2 Automatic Operation

The degree of automation incorporated into the system design is generally dependent upon the complexity of the treatment system, the remoteness of the site, and monitoring and control requirements. An evaluation (trade-off) is usually carried out to compare the initial capital cost of the instrumentation and control equipment and the labor cost savings in system operation.

8.7.3 Unattended 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 PLCs, remote data acquisition, modems, and radio telemetry. System mechanical and electrical components would be selected on the basis of optimum reliability while requiring minimum maintenance and adjustment.

8.8 OPERATION CONCERNS

8.8.1 Equipment quality Problems

Technical problems associated with equipment when used for LFG applications can result due to chlorinated and toxic compounds, particulates, and reduced heating value.

Component malfunctions or breakdowns are undesirable but nevertheless inevitable during the operating lifetime of an LFG recovery system. The best way to react to these setbacks is through a rigorous O&M plan, which not only prevents many problems that might arise out of neglect, but also allows the operator to anticipate, through performance trends, when a particular component is likely to break down. In such a case, the operator can plan ahead by taking the proper measures, whether it be calling a vendor for service or ordering a new part. In this manner, lengthy shutdowns can be largely avoided.

8.8.2 Climate

Climate can play a large role in the day-to-day operation of an LFG system. Temperature fluctuations can result in the natural production of more or less CH_4, which can cause blowers and treatment systems to perform inefficiently. If the landfill is not adequately capped, periods of heavy precipitation can lead to the removal of large volumes of water along with the gas. This water can be harmful to the blowers if not removed, and may require treatment before discharge.

8.8.3 Vandalism

Wellheads and valves should not be exposed to the dangers of tampering, vandalism, or accidental damage. They should be protected by lockable covers with either removable or lockable valve handles.

8.8.4 State Laws

The operator of an LFG facility must know applicable state laws. Most states set their own programs. Many states have regulations more stringent than those in RCRA. A facility can be in compliance with RCRA and still in violation of state law.

8.9 MAINTENANCE REQUIREMENTS

The operation and maintenance (O&M) of an 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, and
- emergency services.

8.9.1 Routine Maintenance

A routine inspection of the entire system should be performed on a regular basis, with the interval depending on the specific system. For example, maintenance and inspection at the blower/flare station is performed weekly. During the inspection, the integrity of the wells and header piping should be visually checked and any damage noted. Pressure and temperature data should also be collected and maintained for key locations throughout the process.

A Routine maintenance program includes periodic maintenance and preventive maintenance.

Periodic maintenance includes testing and checking of the following components:

- extraction wells,
- collection header,
- monitoring wells and probes,
- oil change on blower,
- flame arrestor cleaning,
- condensate handling,
- gas detection system, and
- 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 certain number of hours as recommended by the manufacturers. This will prevent more costly and time-consuming repairs down the line.

Preventive maintenance includes:

- blower bearing lubrication,
- flame sensor cleaning, and
- blower/flare station components.

Regular oil and lubrication changes should also be performed on the blower, compressor, gear box 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.

8.9.2 Non-routine Maintenance

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

- repair or replace failing components,
- testing and adjusting collection system if air intrusion is observed.

8.9.3 Emergence 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,
- execute contingency plans, if required.

8.9.4 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 of record should be calibrated according to manufacturer's recommendations and quality assurance program.

8.9.5 System Adjustment 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 and greater gas generation. Adjustments of flow rate are usually accomplished by partially opening or closing the valve on the blower inlet side.

8.10 SAFETY CONSIDERATIONS

Appropriate safety and health procedures shall be developed and followed for all aspects of LFG recovery installation and operation. The applicability of 29 CFR 1910.120(b) and 29 CFR 1926.65(b) should be determined before enforcing the requirements of this paragraph. Both the contractor and U.S. Army Corps of Engineers (USACE) personnel shall comply with all applicable 29 CFR 1910 and 1926 standards requirements for a contractor Safety and Health Program (SHP) and a Site-Specific Safety and Health Plan (SSHP). The SSHP shall also be developed in accordance with ER 385-1-92. In conjunction with federal regulation compliance, the contractor and USACE personnel shall comply with all pertinent provisions of USACE Safety and Health Requirements Manual, EM 385-1-1. Where there is overlap between the federal requirements and USACE requirements, the contractor shall adhere to the more stringent. In certain instances, state and/or local safety and health requirements may also be applicable. In those instances, the contractor shall be responsible for the knowledge of and compliance with the state and/or local requirements. In all cases, the most stringent of the regulations shall apply.

The SSHP monitoring provisions shall include work area monitoring for the presence of explosive gases which may endanger workers, and otherwise, for the presence of any O_2 depleting or 0_2-displacing gases. The explosive/inert gas monitoring is in addition to the site-specific worker exposure monitoring to be identified in the SSHP for the project. The SSHP provisions shall give special consideration to other safety and health issues unique to LFG applications, including, but not limited to, noise protection (especially around the blowers), adequate ventilation (for indoor blower housings), and temperature extremes (especially during periods of unusually warm or cold weather).

The following guidelines should be followed when working at a landfill in the presence of potentially dangerous gases:

- No person should enter a vault or a trench on a landfill without first checking for the presence of CH_4, CO_2 or other toxic gases. The person should also wear a safety harness with a second person standing by to pull him or her to safety.
- Anyone installing wells in a landfill should wear a safety rope to prevent from falling in the borehole. Open holes should be covered when they are left unattended.
- Smoking should be prohibited on the landfill where drilling, excavation, or installation of equipment is taking place or where gas is venting from the landfill.
- Collected gas from a mechanically evacuated system should always be cleared to minimize air pollution and any potential explosion or fire hazard.
- CH_4 gas in a concentration of 5 to 15 percent is an explosive mixture. Gas accumulations should be monitored in an enclosed structure to insure that explosive conditions are avoided, and if detected, appropriate response is taken to avoid a source of ignition and to vent the structure.

All personnel working on the landfill must be provided training regarding the dangers posed by LFG. Personnel operating safety equipment around the landfill must be thoroughly trained in its use and have a clear understanding of the meaning of observations made with the monitoring equipment. Monitoring equipment must also be periodically calibrated to ensure continued accuracy in the results.

9.0 DESIGN AND CONSTRUCTION PACKAGE

This section describes the USACE regulations applicable to the design and design document components that must be included in the design and construction package. These includes:

- Applicable USACE Design policy and Requirements,
- Design Document Components, and
- Construction Package

9.1 APPLICABLE USACE DESIGN POLICIES AND REQUIREMENTS

The following USACE regulations apply to the development of design documents in their various stages for the USACE:

Regulation	Title
ER 1110-345-100	Engineering and Design - Design Policy for Military Construction
ER 1110-345-700	Engineering and Design - Design Analyses
ER 1110-345-710	Engineering and Design - Drawings
ER 1110-345-720	Engineering and Design - Construction Specifications
ER 1110-2-1150	Engineering and Design - Civil Works
TM 5-814-5	Sanitary Landfill

and other regulations as applicable.

9.2 DESIGN DOCUMENT COMPONENTS

This section outlines the various design packages that are typically required for proper installation and operation. USACE-CEGS guidance specifications, which are typically included in each design document, are listed beneath each design component.

9.2.1 Work Plans

- Safety, Health, and Emergency Response;
- Chemical Data Quality Control;
- Sampling, Analysis, and Disposal of Waste; and
- Air/Gas Monitoring

9.2.2 Background

- Geotechnical characteristics,
- Geohydrological characteristics,
- LFG Gas characteristics,
- Control technology selected,
- Equipment descriptions,
- Monitoring and control, and
- Performance requirements.

9.2.3 Calculations

- Geohydrological calculations;
- Landfill refuse volume;
- Gas phase calculations;
- Number of wells/trenches;
- Radius of influence/distance;
- Equipment sizing (pipe header, blowers, pumps, valves);
- Condensate volume; and Utility requirements.

9.2.4 Records

- Data for refuse disposal,
- Aerial map of landfill,
- LFG elevation Map,
- Equipment literature/catalog, and
- Environmental performance criteria.

9.2.5 Construction Plans and Drawings

Plans. Construction plans include:

- Location map,
- General plan,
- Landfill sampling points used in the investigation,
- Equipment layout plan,
- Wells/piping plans,
- Electrical distribution plan, and
- Site control plan,

Drawings. Construction drawings include the following:

- Process Flow Diagrams;
- Process and Instrumentation Diagrams;
- Civil drawings;
  - Locations of wells,
  - Locations and sizes of all header lines and pipe Support (if aboveground),
  - Locations of all in-line isolation valves,
  - Locations of all condensate knock-out pots,
  - Locations of treatment system,
  - Locations of condensate force Main,
  - Locations of all monitoring probes,
  - Details of gas extraction well construction,
  - Details of monitoring probe construction,
  - Details of condensate sump construction,
  - Details of in-line isolation valves and monitoring stations, and
  - Wells sections and details;

- Mechanical Drawings:
  - Locations of pumps for condensate,
  - Locations of storage tanks for condensate,
  - Locations of blowers,
  - Details of flare Unit,
  - Details and schedule for condensate sump pumps,
  - Details of condensate holding tanks, and
  - Schedule of pipes and fittings;

- Electrical Drawings:
  - Locations of power distribution to be constructed on-site,
  - Electrical duct and conduit schedule,
  - Electrical one-line diagram for the flare support building and flare,
  - Heat trace panel wiring diagram, if applicable,
  - Control panel layout with control switches, and
  - All necessary legends and schedules.

- Utility Drawings:
  - Electricity,
  - Air, water and telephone

9.2.6 Equipment Drawings

Major System Components

- Flare
- Blower,
- I.C. Engine, if applicable,
- Incinerator, if applicable,
- Scrubber, if applicable, and

Accessories

- Condensate pumps,
- Storage and process vessels,
- Piping,
- Valves, and
- Chemical feed systems.

Special Items

- Flame arrestors,
- Heat sensors, and Thermocouples.

9.3 OTHER REQUIREMENTS

- Contract close-out,
- Contract quality control,
- Temporary construction facilities, and
- Environmental protection.

9.4 CONSTRUCTION PACKAGE

In addition to the documents listed in previous Sections 9.2, 9.3, and 9.4 in the design documents, the construction package will include, as a minimum, the following documents:

9.4.1 Construction Specifications

- Invitation for bids,
- Information for bidders,
- Statement of Bidders's Qualifications,
- Contract Agreement,
- Performance Bond,
- General Conditions,
- Special Conditions,
- Construction Specifications, and
- Equipment Specifications.

9.4.2 USACE Guide Specifications

CEGS Number	Title	Date
01030	Metric Measurements	Sep 93
01110	Safety, Health and Emergency Response	Apr 94
02685	Gas Distribution System	Dec 93
15250	Thermal Insulation for Mechanical Systems	Jul 89
15488	Gas Piping Systems	Jan 89
16370	Electrical Distribution System, Aerial	Jan 93

CEGS Number	Title	Date
16375	Electrical Distribution System, Underground	Nov 92
15330	Wet Sprinkler Systems	Jun 94
16665	Static Electricity Protection System	Jul 89
16670	Lightning Protection System	Dec 88

APPENDIX B
DESIGN CALCULATIONS

1.0 INTRODUCTION

This appendix presents a description of the general types of calculations that may be required for LFG applications. The calculations described refer primarily to the off-gas collection systems. Additional calculations may be necessary for specific type of LFG collection and treatment technology or for specific types of equipment selected. Several of these calculations are dependent on, or should be used in conjunction with, other calculations that should be performed or used in the development of the design for the entire treatment process or treatment facility. Design examples illustrating the use of several of these calculations are presented in Appendix E.

2.0 PURPOSE

The primary purpose of the design calculations is to provide design criteria for sizing equipment, editing guide specifications and developing construction drawings. Based on the preliminary selection of equipment, additional calculations can also be performed to determine parameters such as utility requirements and supporting mechanical and electrical distribution systems.

3.0 DESIGN CALCULATIONS

3.1 ASSUMPTION OR DEFAULT VALUES

Gas Production

Methane (CH_4) generation rate: Estimated by the Scholl Canyon model.

LFG generation rate: Twice the methane generation rate.

Gas Characteristics

CH_4 concentration of the LFG: 50 percent.

Extraction Well Design

Default vacuum pressure at each extraction well:
1.01×10^5 N/m^2 (.9928 atm)

The depth of the extraction wells is 75 percent that of the landfill depth.

Blower System

Capacity of blower, Q_c = $m^3.min^{-1}$ ($35.30ft^3.min^{-1}$)

Maximum gas velocity, V = 914.4 m/mm (2000 ft/mm)
through the piping.

Condensate System

Condensate is calculated based on LFG enters collection system at 100 percent saturation. Cools to 12.7^0C (55^0F)

3.2 CALCULATION FORMULAE

3.2.1 Estimation of LFG Generation Rate

$$Q = 2 * k * L * R^{-k(t-tag)} \qquad (1)$$

where,

Q = LFG generation rate at time t, m^3/yr (ft^3/yr)
k = refuse decay rate, 1/yr
L = potential gas generation capacity, m^3/ton (ft^3/ton)
R = refuse acceptance rate, tons/yr
t = time since refuse placement, years
lag = time to reach anaerobic conditions, years

3.2.2 Radius of Influence, ROI

$$ROI = (Q_{wDESIGN} Capacity/\pi L \rho_{refuse} Q_{gen}{}^{1/2} \qquad (2)$$

where,

ROI = radius of influence, m
$Q_{wDesign}$ = design LFG generation rate, m^3/yr
Capacity = design capacity of the landfill, kg
B = 3.14
D_{refuse} = refuse density, kg/m^3
Q_{gen} = peak LFG generation rate, m^3/yr
L = landfill depth, m

3.2.3 Landfill Pressure, P_L

$$P_L = [(\frac{P_v\ (ROI^2 \ln\ (ROI/r)\ \mu_{lfg}\ \rho_{refuse}\ Q_{gen}}{Design\ Capacity\ K_{refuse}\ (WD/L)} * 3.15\ x\ 10^{-7}) + P_v^2]^{1/2} \tag{3}$$

where,

P_L = landfill pressure, KN/cm^2
ROI = radius of influence, m
Pv = vacuum pressure at the well head, KN/m^2
r = radius of outer well (or gravel casing), m
D_{refuse} = refuse density, 650 kg/m^3
k_{refuse} = intrinsic refuse permeability, m^2
μ_{lfg} = LFG viscosity, Newton-sec/m2
Design Capacity = design capacity of the landfill, kg
WD = well depth (i.e., 0.75L), m
L = landfill depth, m
Q_{gen} = peak LFG generation rate, m^3,yr

3.2.4 Optimal Number of Extraction Wells, $Wells_{TOT}$

$$Wells_{TOT} = (\text{Landfill surface area})/B.(ROI)^2 \tag{4}$$

where,

$wells_{TOT}$ = total number of wells required
B = 3.14
ROI = radius of influence, m

3.2.5 Header Pipe sizing

$$\text{Diameter} = \frac{\text{Mass flow rate, kg/hr}}{\text{LFG denity, kg/m}^3}$$

or

$$\text{Diameter}^{(17)} = 1.414 * (W^{0.408}/D^{0.343}) \tag{5}$$

where,

W = LFG mass flow rate, (1,000 lb/hr)
D = LFG density (lb/ft^3)
1.414 = conversion factor

or

$$\text{Diameter} = W /2000\ ft.sec^{-1} \tag{6}$$

where,

W = LFG mass flow rate, (1,000 lb/hr)
2,000 = minimum LFG velocity in the piping, ft/sec

3.2.6 Pipe head-loss

$$h_L = \frac{fL}{d} \times \frac{V^2}{2g} \qquad (7)$$

where,

hL = Head loss, m (ft)
L = Length of segment, m (ft)
f = Friction factor for the pipe
d = Inside diameter of the pipe
V = Velocity of the flow, m/sec (ft/sec)
g = Acceleration due to gravity, 9,81 m/sec (32.2 ft/sec).

The friction factor f is based on the Reynolds Number (R_e) and the roughness of the header pipe. Moody Diagramx is used to estimate friction factor based on R_e.

3.2.7 Motor horsepower requirement

$$W_{SM} = \frac{Q_{TOT}\,(\Delta P_{TOT})}{3.1536 \times 10^7\,(.65)} \qquad (8)$$

where,

W_{SM} = watt
Q_{TOT} = total gas producton rate, m^3/min
P_{TOT} = total system pressure drop, N/m^2
.65 = motor efficiency

3.2.8 Number of Blowers required

$$No.\ Blowers = Q_{TOT}/(283.2\ m^3/min) \qquad (9)$$

where,

Q_{TOT} = total gas production rate, m^3/min
283.2 m^3/min = maximum blower flow rate

3.2.9 Condensate Flowrate, Q_{cond}

$$Q_{cond} = \frac{.0203\ Q_{TOT}}{760 - 1.87 \Delta P_{TOT}} \tag{10}$$

Where,

Q_{cond} = flow rate of condensate, m^3/min

Q_{TOT} = total gas production rayte,m^3/min

)P_{TOT} = total system pressure drop, N/m^2

Alternatively, condensate can be calculated by assuming:

100% relative humidity
Density of condensate = Density of water
Piping temperature 55°F

Calculations are as follows:

Calculations are as follows:

1. Water concentrations (# water/cu.ft wet air)= Humidity(# water/# dry air) * (Specific volume (cu.ft/# dry air)

2. Volume of water extracted (gal/day) = water concentration (#/cu.ft)*flow rate (cfm) * 1440 min/day)* 0.12 (gal/#)

3. Volume of water condensed (gal/day) = Volume of water extracted at °F - volume of water extracted at 55°F.

4.0 UTILITY CALCULATIONS

4.1 POWER REQUIREMENTS

Several types of calculations for power requirements can be used in the design of an LFG application including a normal load and lead protection analysis, a ground fault current analysis, and lighting analysis. These types of calculations are usually performed as part of the electrical calculations provided for the entire treatment facility.

4.2 Water Requirements

Systems that typically require potable water include:

- sanitary,
- emergency shower and eye wash, and
- fire water.

Based on the specific requirements for each of these applications, calculations will be performed for the quantity of potable water required and associated distribution systems.

4.3 Air Requirements

The calculations that are performed for the air system include those for sizing the air compressors and those for sizing air distributions systems.

Additional calculations performed for the distribution systems include those required for sizing air receivers, air dryers, and the distribution piping system. These calculations are primarily based on the specific air requirements for each individual demand.

5.0 ADDITIONAL REQUIREMENTS

In addition to the process, mechanical, and electrical calculations, additional design requirements and calculations that may be required for LFG applications include those related to architectural requirements such as the determination of aisle space, equipment clearances, and storage space; structural requirements for the purification units, supporting accessories, and chemical storage; and operation and maintenance provisions. However, these types of calculations are application-specific; therefore, no specific calculations are provided in this Appendix.

APPENDIX C

LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienist
AFBMA	Anti-Friction Bearing Manufacturers Association
AISI	American Iron and Steel Institute
ANSI	American National Standard Institute
API	American Petroleum Institute
ARAR	Applicable or Relevant and Appropriate Requirement
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BPTCA	Best Practicable Technology Currently Available
CAA	Clean Air Act - The law that authorizes regulations regarding releases of air borne contaminants from stationary and non-stationary sources.
CO	Carbon monoxide
$C0_2$	Carbon dioxide
CWA	Clean Water Act - The law which authorizes regulation of discharges of water such as landfill gas condensate.

CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act.
CFR	Code of Federal Regulations
COD	Chemical Oxygen Demand
DOT	Department of Transportation
e	In math, the base of the natural system of logarithms having a numerical value of 2.71828
EM	Engineering Manual
ER	Engineering Regulation
EPA	U.S. Environmental Protection Agency
FS	Feasibility Study
gpd	Gallon Per Day
gpm	Gallon Per Minute
Groundwater	1: Water below the land surface in the zone of saturation, or 2: Water in the saturated zone or stratum beneath the surface of land or water.
GSA	Geological Society of America
Halogen	Any group of 5 chemically-related, non-metallic elements that includes bromine, fluorine, chlorine, iodine, and astatine.

Hazardous Waste	A solid waste (as defined by 40 CFR Part 261.3) is a hazardous waste (as defined in 40 CFR Part 261.3) if it is not excluded as a hazardous waste by regulation and it meets the criteria (40 CFR Subpart C) of reactivity, corrosivity, ignitability or toxicity or as a listed waste as defined in 40 CFR Part D.
Hydrocarbon	Any of vast family of compounds containing carbon and hydrogen in various combinations found in fossil fuels.
HTW	Hazardous and Toxic Waste
ID	Inside diameter
Inorganic matter	Chemical substances of mineral origin, not containing carbon-to-carbon bonding. Generally structured through ionic bonding.
Industrial Waste	Any solid, semi-solid, or liquid waste generated by a manufacturing or processing plant.
Independent Laboratory	A test facility operated independently of any product manufacturer capable of performing evaluation tests. Additionally, the laboratory shall have no financial interests in the outcome of these tests other than a fee charged for each test performed.
IR	Infrared
Kinetic rate	The moles of chemical species produced by chemical reaction per volume per unit time.

kW	Kilowatt
kWh	Kilowatt-hour
Leachate	Any liquid, or suspended components that has percolated through or drained from a hazardous waste or non-hazardous landfill
MCX	Mandatory Center of Expertise
mm	Millimeter
mL	Milliliter
mg/L	Milligrams per liter (or parts per million in water)
μg/L	Micrograms per liter (or parts per billion in water)
NESHAP	National Emission Standards for Hazardous Air Pollutants promulgated under the Federal Clean Air Act (40 CFR Part 61 and 63).
Neutralization	Mixing acid and basic materials such that the net effect is a near-neutral pH.
NIOSH	National Institute for Occupational Safety and Health
NMOC	Non methane organic compound
NO_x	Nitrogen oxides
NPDES	National Pollutant Discharge Elimination System
NPT	Normal Temperature and Pressure which corresponds to 0^0C (32^0F) and 1 atmosphere

O_2	Oxygen
Organic Materials	Chemical compounds of carbon excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides, metallic carbonates and ammonium carbonate.
On-Site Disposal	The areal extent of contamination and all suitable areas in very close proximity to the contamination necessary for implementation of the response action.
O&M	Operation and Maintenance
OSHA	Occupational Safety and Health Administration (of the Department of Labor)
ORP	Oxidation-Reduction Potential
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Polychlorinated Biphenyl
ph	A measure of the acidity or alkalinity of a solution, numerically equal to 7 for neutral solutions, increasing with alkalinty and decreasing with increasing acidity. The unit of pH is universal unit and equal to the logarithm, at base 10, of the reciprocal of the concentration of H+ in mole/L, or $pH=1/[H^+]$
PLC	Programmable Logic Controller - a solid-state control system that has a user programmable memory for storage of instruction such as: I/O control logic timing, counting, arithmetic and data manipulation. The PLC can be used as

	direct replacement for electromechanical control relays.
<u>PM</u>	Particulate matter
<u>POTW</u>	Publicly-Owned Treatment Works
<u>ppm</u>	Parts Per Million
<u>QA/QC</u>	Quality Assurance/Quality Control
<u>ROG</u>	Reactive Organic Gases
<u>RCRA</u>	The Resource Conservation and Recovery Act
<u>SVOC</u>	Semivolatile Organic Compound
<u>TLX</u>	Threshold Limit Value
<u>TOC</u>	Total organic carbon
<u>TSCA</u>	Toxic Substances Control Act
<u>Turbidity</u>	A cloudy condition in water due to suspended silt or organic matter.
<u>VOC</u>	Volatile Organic Compound, defined as: 1) any compound containing carbon and hydrogen in combination with any other element which has a vapor pressure of 1.5 pounds per square inch absolute (77.6 mm Hg) or greater under actual storage conditions 2) Any organic compound which participates in atmospheric photochemical reactions except for those designated by EPA Administrator as having negligible photochemical reactivity.

APPENDIX D
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APPENDIX E
DESIGN EXAMPLES

The following hypothetical example illustrates the approach and procedure used for the calculation and design of a landfill gas collection system for a 12-acre municipal landfill. This model can be used for mixed and hazardous waste landfills, however, consideration for the composition of the refuse must be factored into the calculations for gas production potential as well as the handling of off-gas.

The following example is hypothetical. The following parameters for the hypothetical site were selected:

<u>Site Characteristics</u>

- Landfill Footprint: 12 acres
- Maximum Depth at Center point: 70 feet
- Landfill Side Slope: 3:1 horizontal:vertical
- Landfill Top Slope: 5 %
- Landfill cover area: 620,000 ft^2

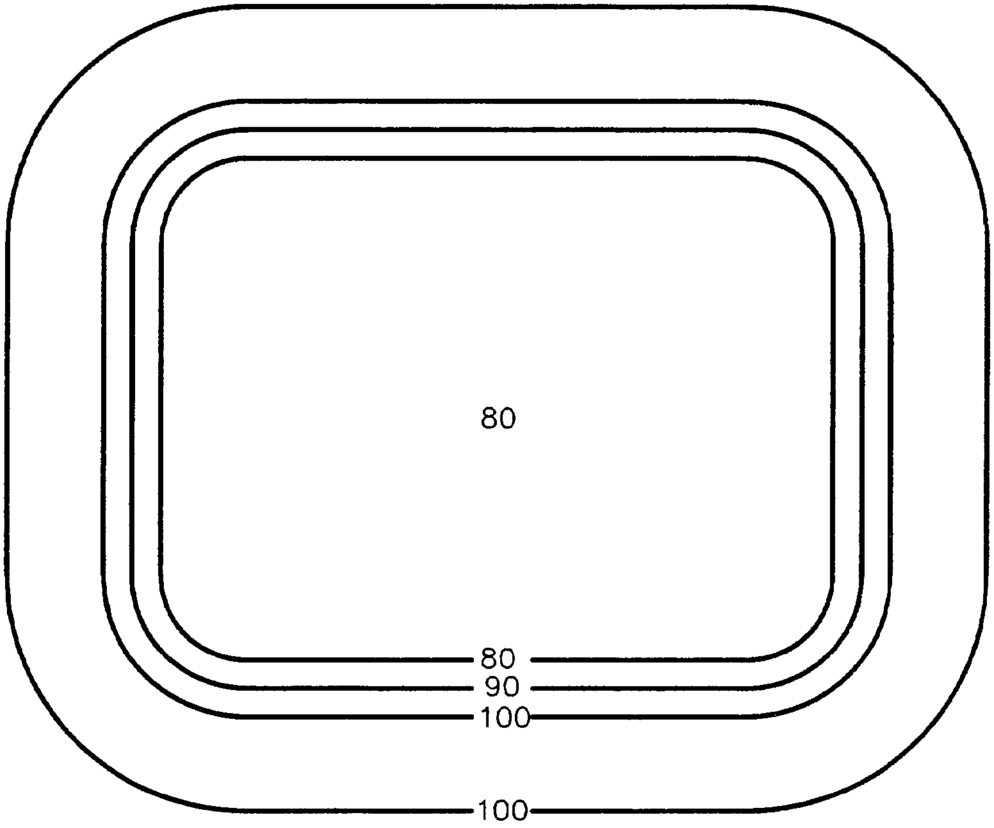
<u>Refuse Characteristics</u>

- Ratio of Refuse/Cover Material: 4:1
- Age of Refuse: 20 years
- In-Place Refuse Density: 800 #/yd^3
- Capping Material: 40 mil HDPE
- Refuse Void Ratio: 4 %

<u>Gas Characteristics</u>

- Gas Constant: 0.08 yr^{-1}
- Gas Production Potential: 7400 ft^3/ton
- Concentration of Methane in Gas: 50 %
- Radius of Influence/Well: 200 ft
- Vacuum Pressure at Wellhead: 10 in wc
- Temperature of Landfill Gas: 110 ^{0}F
- Landfill Gas Viscosity: 2.8E-7 lbs.sec/ft^2
- Landfill Gas Density: 7.6E-2 lbs/ft^3

Figure E-1 illustrates the Model Landfill Base Grade Plan.



BASE GRADE PLAN

FIGURE E-1

MODEL LANDFILL
N.T.S.

1. Estimate Volume of Refuse in Landfill

Assumptions:

! Pre-landfill development topography and final topography are available, see E-l,

! No historical records are available for estimating rate of filling at the site

Methodology:

! Calculate landfill volume using geometry or computer-aided design software

! Estimate in-place volume of refuse based on ratio of waste: cover material

! Estimate tonnage of refuse based on estimated refuse density

Calculations

Compute landfill volume using computer aided design (CAD) software.

Datum (DTM) to Datum Volume
Cut and Fill Volumes
CAD Output

Shrinkage/swell factors:		Cut: 1.0000	Fill: 1.0000
Original DTM Layer Name	# of Points	Final DTM Layer Name	# of Points
EG	176	FG	400

Cut Volume (CY)	Cumulative Cut Volume	Fill Volume (CY)	Cumulative Fill Volume
0.0	0.0	872,826.6	872,826.6

Volume of Refuse Calculation:

Total cumulative fill volume = 872,827 CY

Assuming a-12" intermediate/final cover is currently constructed across entire landfill area.

-Volume of Intermediate/Final Cover:

$620{,}000\ \text{ft}^2 \times \text{lft} \times \frac{\text{CY}}{27\ \text{ft}^3} =$ 22,962 CY

Assuming there are 6 layers of refuse.

-Total cover material:

22,962 CY x 6 - 137,772 CY

-Volume of Refuse:

872,827 CY - 137,772 CY = 735,055 CY

Assuming refuse density of 800#/CY (poorly compacted)

-Tonnage of refuse:

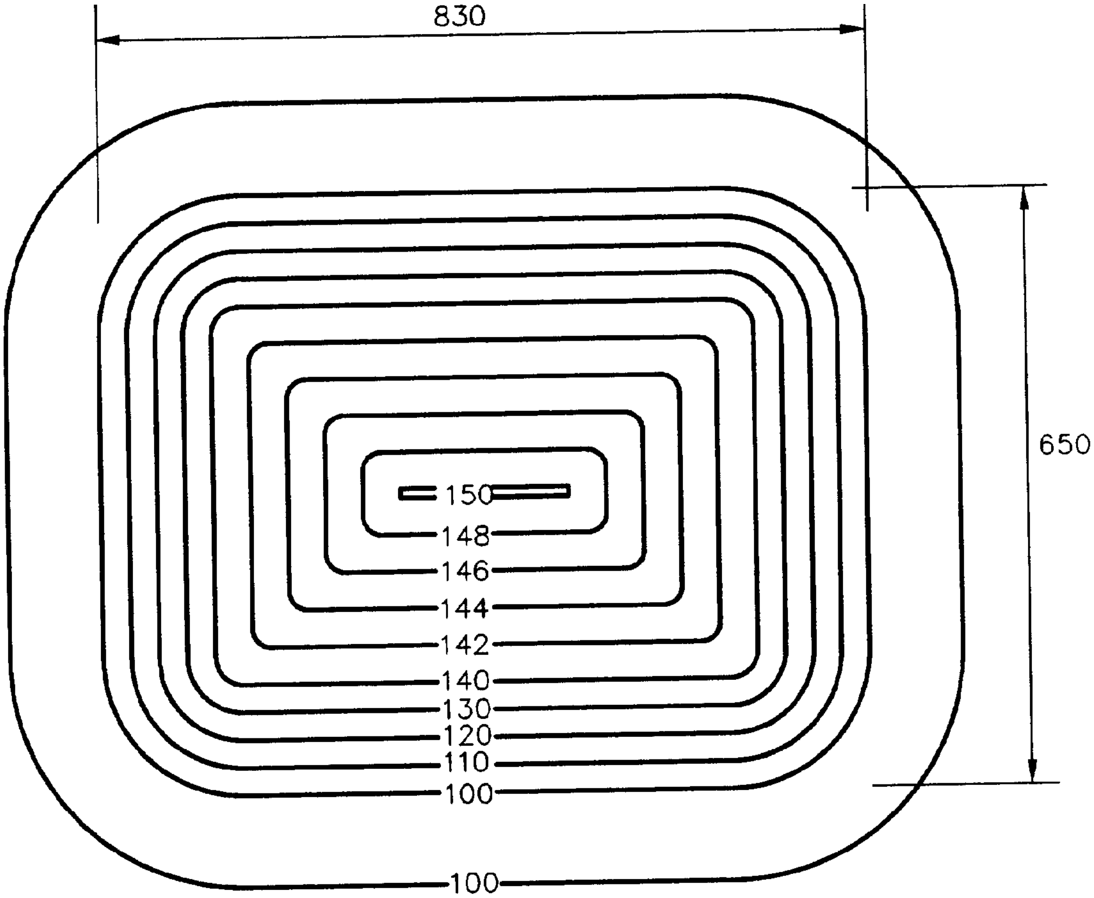
$735{,}055\ \text{CY} \times \frac{800\#}{\text{CY}} \times \frac{\text{lton}}{2000\#} =$ 294,022 ton

Assuming regular increment of refuse displacement over 15 year life of landfill.

-Annual refuse acceptance to landfill:

$\frac{294.022\ \text{ton}}{15\ \text{yr}} =$ 19,600 ton/yr

The Model Landfill Final Fill Plan is illustrated in Figure E-2.



FINAL FILL PLAN

FIGURE E-2

MODEL LANDFILL
N.T.S.

2. Estimation of Landfill Gas Generation

Assumptions:

- Waste composition can be approximated by average municipal waste composition data compiled by the U.S. EPA

- Landfill setting is a humid environment establishing conditions affecting biological degradation

- Landfill gas generation is due principally to anaerobic bacteria and can be simulated by first order kinetics

Methodology:

- Use Scholl Canyon Model assuming waste was deposited in equal increments annually over the active life of the landfill

- Assume refuse was deposited at regular increments over the 15-year period

3. Gas generation rate calculation

Method 1: SCHOLL CANYON MODEL

Formula: Q = 2*[k*L*R[exp(-K*(t-lag))]

where:

Q = landfill gas generation rate @ time t (ft^3/yr).
L = potential gas generation capacity of refuse (ft^3/ton)
R = annual refuse acceptance rate in landfill (tons/yr)
k = gas generation rate, or refuse decay rate (1/yr)
t = time since refuse placement (yr)
lag = time to reach anaerobic conditions (yr)

Input parameters:

L = 7400	Year closed	=	1990
k = 0.08	Current Year	=	1995
lag = 2	Time Since Closure	=	5
	Avg. refuse	=	18,620 ton yr

Year	Time Since Refuse placement	Generation Date 1995
1975	20	5.22E+06
1976	19	5.66E+06
1977	18	6.13E+06
1978	17	6.64E+06
1979	16	7.19E+06
1980	15	7.79E+06
1981	14	8.44E+06
1982	13	9.14E+06
1983	12	9.91E+06
1984	11	1.07E+07
1985	10	1.16E+07
1986	9	1.26E+07
1987	8	1.36E+07
1988	7	1.48E+07
1989	6	1.60E+07
1990	--	0.00E+00
1991	--	0.00E+00
1992	--	0.00E+00
1993	--	0.00E+00
1994	--	0.00E+00
1995	--	0.00E+00
TOTAL ANNUAL CURRENT PRODUCTION		1.46×10^8 ft^3/yr 4.13×10^6 m^3/yr 7.86m^3/min

4. Radius of Influence/Well System Layout&

Assumptions:

! No pilot scale test data is available

Methodology:

! Use EPA default diameter of influence of 200'

! Divide landfill area by area of influence of one well to obtain number of wells

! Establish layout of wells using the estimated coverage of each well predicted by the 200' diameter of influence

Well System Layout Calculation:

Assume:

Surface Area $\approx$ 620,000 ft^2
Diameter of Influence = 200 ft
Area of Influence = $\frac{Bd^2}{4} = \frac{B(200)^2}{4} = 31{,}400 ft^2$

$$\text{Number of Wells Required} = \frac{\text{Area of Landfill}}{\text{Area of Influence}}$$

$$= \frac{620\ 000\ ft^2}{3l{,}400 ft^2} = 19.74 \text{ say 20 Wells}$$

Well System layout is presented in Figure E-3.

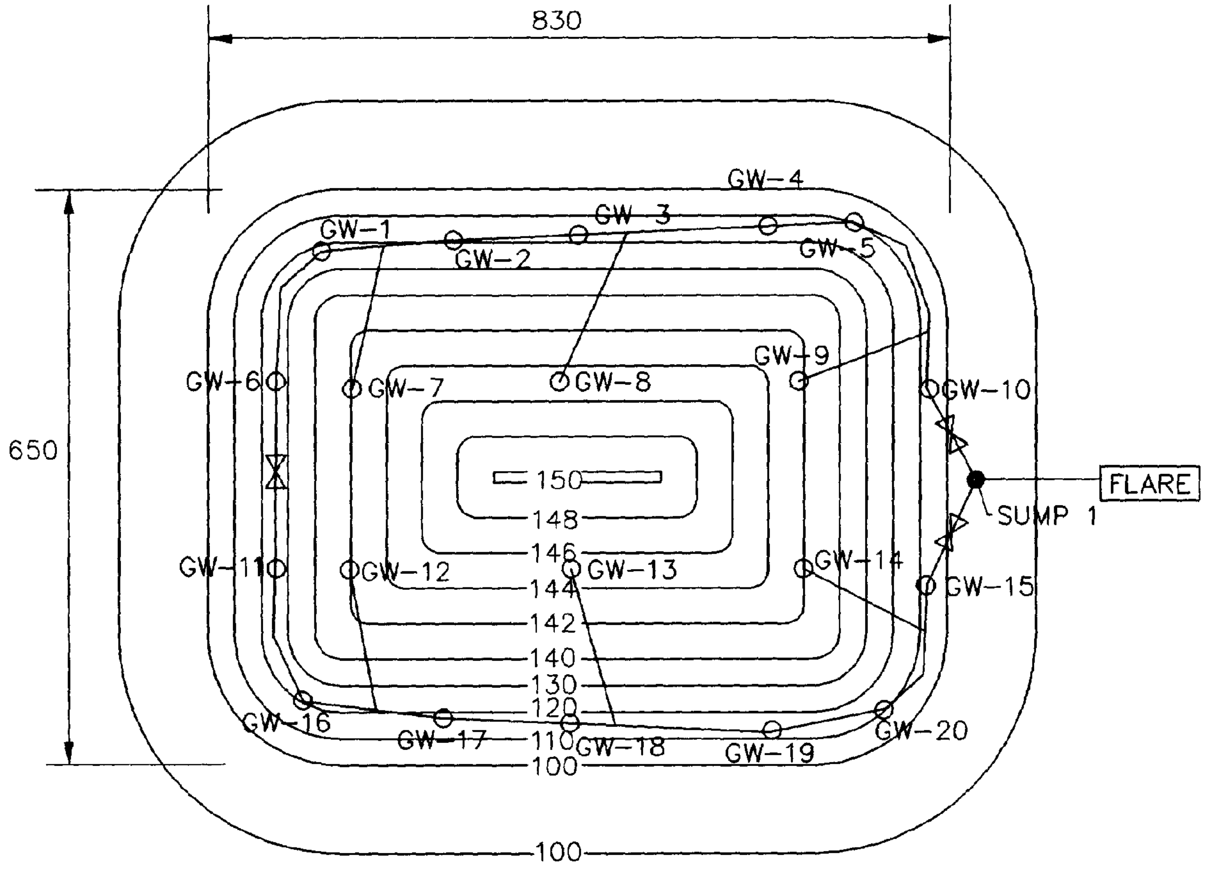


FIGURE E-3

MODEL LANDFILL
GAS WELL SYSTEM LAYOUT

LEGEND

○ GAS EXTRACTION WELL

● SUMP

— GAS LATERAL

⋈ IN-LINE ISOLATION VALVE/
MONITORING STATION

Radius of Influence Equation - Intrinsec Permeability

Input Variable	Unit	Wells	
		G-12	G-16
Landfill Depth, L	ft	65	45
Landfill Capacity, M	lbs	5.59E+06	5.59E+06
Screen Length, WD	ft	55	35
Ratio of well depth to landfill depth, WD/L	ft/ft	0.85	0.78
Efficiency of Collection, Ea	%	100	100
Flowrate, Q	cfm	277	277
Viscosity of landfill gas, mu	lb min/ft^2	4.21E-09	4.21E-09
Density of refuse, rho	lb/ft^3	29.63	29.63
Extraction well radius, r	ft	0.75	0.75
Maximum well vaccuum (gage), Pv	lbs/ft^2	26.02	26.02
Internal pressure of landfill (gage), PI	lbs/ft^2	21.2	21.2
Radius of Influence, R	ft	100	100
Output Variable Intrinsic permeability of refuse, k	ft^2 (m^2)	4.07E-08	4.43E-08

EQUATIONS: (PI^2 -Pv^2)/Pv = (R^2 ln(R/r) mu rho Q Ea)/ (M k (WD/L))
solve for k: k = (R^2 ln(R/r) mu rho Q (Ea/100))/((PI^2 - Pv^2)/Pv) M (WD/L))

6. Sizing of Header Pipe in Gas Collection system

Assumptions:

- Minimum pipe diameter is 4 inches
- Pipe is constructed of HDPE or similar polymer

Methodology:

- Estimate cumulative gas flow rates for each length of header
- Estimate diameter of header assuming use of a minimum velocity through the header system (2000 ft/s)
- Divide cumulative gas flow rate for each length of header by 2000 ft/s to establish the diameter of the pipe

Calculations:

The Gas Extraction Well System Calculations can be found on pages E-12 thru E-14.

7. Sizing of Landfill Gas Blower

Assumptions.

- Gas parameters as noted above
- Relative roughness of HDPE pipe can be approximated by the relative roughness of "smooth pipes" on the Moody Diagram(14).
- Fittings losses as obtained from manufacturer's data

Methodology

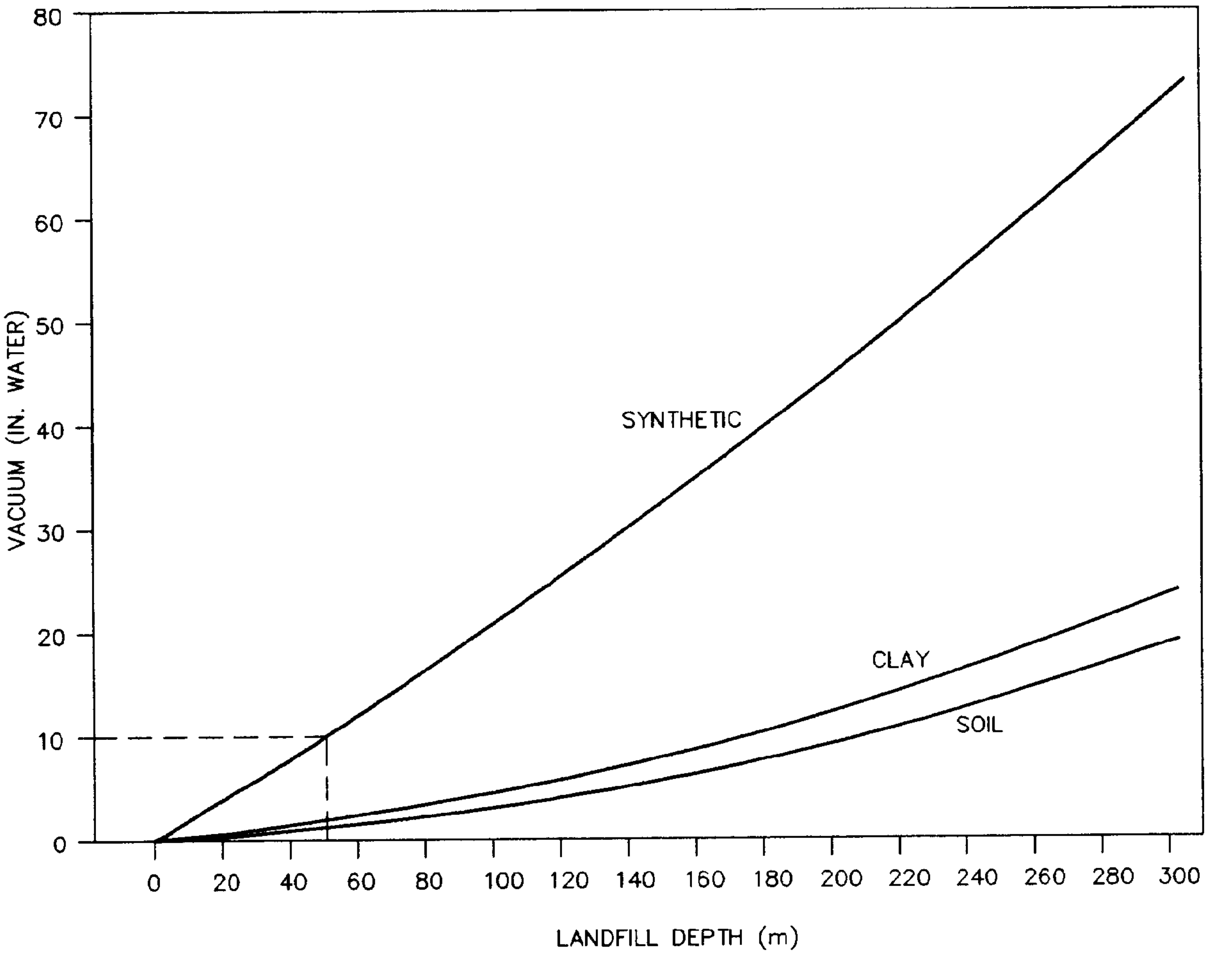
- Calculate the velocity through each header section
- Calculate velocity head for each header section
- Estimate head loss due to friction for each header section
- Estimate vacuum at the well head using figure E-4
- Estimate fitting losses

MODEL LANDFILL
GAS EXTRACTION WELL SYSTEM CALCULATIONS

(1) Well Designation	(2) Well Screen Length* (ft)	(3) Estimated Flowrate per Well (cfh)	(4) Estimated Cumulative Flowrate (cfh)	(5) Lateral Section Designations	(6) Length of Lateral (ft)	(7) Lateral Diameter (1) (in)	(8) Lateral Diameter (2) (in)	(9) Selected Lateral Diameter
GW-6	30	846			160			
GW-1	28	790	846	FA	160	1.1	1.1	4
GW-7	26	733	1636	AB	160	1.5	1.6	4
GW-2	24	677	2369	BC	160	1.7	1.9	4
GW-3	41	1156	1156	G-A'	160	1.3	1.3	4
GW-8	22	620	2989	CD	160	1.9	2.1	4
GW-4	43	1213	1213	H-C'	160	1.3	1.4	4
GW-5	20	564	3553	DE	160	2	2.3	6
GW-9	41	1156	1156	I-E'	160	1.3	1.3	4
GW-10	17	479	4709	EJ	160	2.2	2.7	6
			5188	JU	125	2.3	2.8	6
GW-11	30	846						
GW-16	28	790	846	KP	160	1.1	1.1	4
GW-12	26	733	1636	PQ	160	1.5	1.6	4
GW-17	24	677	2369	QR	160	1.7	1.9	4
GW-18	41	1156	1156	L-Q'	160	1.3	1.3	4
GW-13	22	620	2989	RS	160	1.9	2.1	4
GW-19	43	1213	1213	M-R'	160	1.3	1.4	4
GW-20	20	564	3553	ST	160	2	2.3	6
GW-14	41	1156	1156	N-T'	160	1.3	1.3	4
GW-15	17	479	4709	TO	160	2.2	2.7	6
			5188	OU	125	2.3	2.8	6
SUMP								
U			10376	TO FLARE	100	3.1	4	8
TOTALS								

(1) Well Designation	(10) Gas Velocity per Well (ft/s)	(11) Gas Velocity (ft/s)	(12) Reynold's Number (NR)	(13) Friction Factor (f)	(14) Velocity Head per Well (in. H2O)	(15) Cummulative Velocity Head (in. H2O)	(16) Head Loss due to Friction (in. H2O)
GW-6	2.69						
GW-1	2.52	2.69	6.85E+03	0.02	0.001	0.002	0.019
GW-7	2.33	5.21	1.33E+04	0.02	0.001	0.006	
GW-2	2.16	7.54	1.92E+04	0.02	0.001	0.012	0.115
GW-3	3.68	3.68	9.37E+03	0.02	0.003	0.003	0.029
GW-8	0.88	9.52	2.42E+04	0.02	0	0.019	0.182
GW-4	3.86	3.86	9.83E+03	0.02	0.003	0.003	0.029
GW-5	0.8	5.03	1.92E+04	0.02	0	0.005	0.032
GW-9	3.68	3.68	9.37E+03	0.02	0.003	0.003	0.029
GW-10	0.68	6.67	2.55E+04	0.02	0	0.009	0.058
		7.34	2.80E+04	0.02		0.011	0.055
GW-11	2.69			0.02	0.002		
GW-16	2.52	2.69	6.85E+03	0.02	0.001	0.002	0.019
GW-12	2.33	5.21	1.33E+04	0.02	0.001	0.006	0.058
GW-17	2.16	7.54	1.92E+04	0.02	0.001	0.012	0.115
GW-18	3.68	3.68	9.37E+03	0.02	0.003	0.003	0.029
GW-13	0.88	9.52	2.42E+04	0.02	0	0.019	0.182
GW-19	3.86	3.86	9.83E+03	0.02	0.003	0.003	0.029
GW-20	0.8	5.03	1.92E+04	0.02	0	0.005	0.032
GW-14	3.68	3.68	9.37E+03	0.02	0.003	0.003	0.029
GW-15	0.68	6.67	2.55E+04	0.02	0	0.009	0.058
		7.34	2.80E+04	0.02	0	0.011	0.055
SUMP							
U	5.29	8.26	4.21E+04	0.02	0.006	0.014	
TOTALS							1.154

(1) Well Designation	(17) Fitting Losses Tee #	(17) Tee Loss	(18) Valves #	(18) Valves Loss	(19) Sumps/ Monitoring Stations	(20) Total Losses
GW-6			1	0.00163		0.00163
GW-1			1	0.00142		0.02042
GW-7			1	0.00122		0.05922
GW-2			1	0.00104		0.11604
GW-3	1	0.006	1	0.00304		0.03804
GW-8			1	0.00015		0.18215
GW-4	1	0.006	1	0.00334		0.03834
GW-5			1	0.00013		0.03213
GW-9	1	0.006	1	0.00304		0.03804
GW-10			1	0.00009		0.05809
						0.055
GW-11			1	0.00163		0.00163
GW-16			1	0.00142		0.02042
GW-12			1	0.00122		0.05922
GW-17			1	0.00104		0.11604
GW-18	1	0.006	1	0.00304		0.03804
GW-13			1	0.00015		0.18215
GW-19	1	0.006	1	0.00334		0.03834
GW-20			1	0.00013		0.03213
GW-14	1	0.006	1	0.00304		0.03804
GW-15			1	0.00009		0.05809
			1	0		0.055
SUMP					0.41	
U					0.41	0.41
TOTALS		0.036		0.02857	0.82	1.68657



MAXIMUM BLOWER VACUUM AS A FUNCTION OF LANDFILL DEPTH FOR THREE COVER TYPES

FIGURE E-4
N.T.S.
(SOURCE 3)

Gas Extraction well System Calculations

Methodology:

- Total losses for collection system
- Estimate losses for treatment system and establish delivery pressure for treatment unit
- Calculate horsepower requirement for the blower from total losses
- Use manufacturer's information to select blower that can meet both head and flow rate requirements

Calculations:

Calculations for sizing are shown below and on the following pages.

Motor Horse Power Requirements:

$$W_{SM} = \frac{Q_{TOT}\,(\Delta P_{TOT})}{3.1536 \times 10^7\ (.65)} \qquad (8)$$

$Q_{TOT} = 1.46\text{x}10^8 \frac{ft^3}{yr} \text{ x } \frac{m^3}{35.31ft^3} = 4.13\text{x}10^6 \frac{m^3}{yr}$

ΔP_{TOT} = landfill cover pressure drop + pipe header losses + treatment system losses, asumming 5 in.wc

= 10in.wc/well x 20wells + 1.22 + 1.69 + 5 = 207.91 in.wc

$= 207.91 \text{ in.wc x } \frac{10^5 N.m^{-2}}{1020 in.wc} = 20{,}380\ N.m^{-2}$

$W_{SM} = (4.13 \text{ x } \underline{10^6 m^3} \text{ x } 20{,}380\ N.m^{-2})/3.154\text{x}10^7\text{x}0.65) = \underline{4{,}111 \text{ Watts}}$

$4{,}111 \text{ W x} \frac{HP}{746 \text{ W}} = 5.5 \text{ HP}$

Electric motors come with standard sizes, 5 7.5 HP, therefore use 7.5 HP motor.

Blower specification: 175 cfm @ 7.5 HP (add 1 blower as spare)

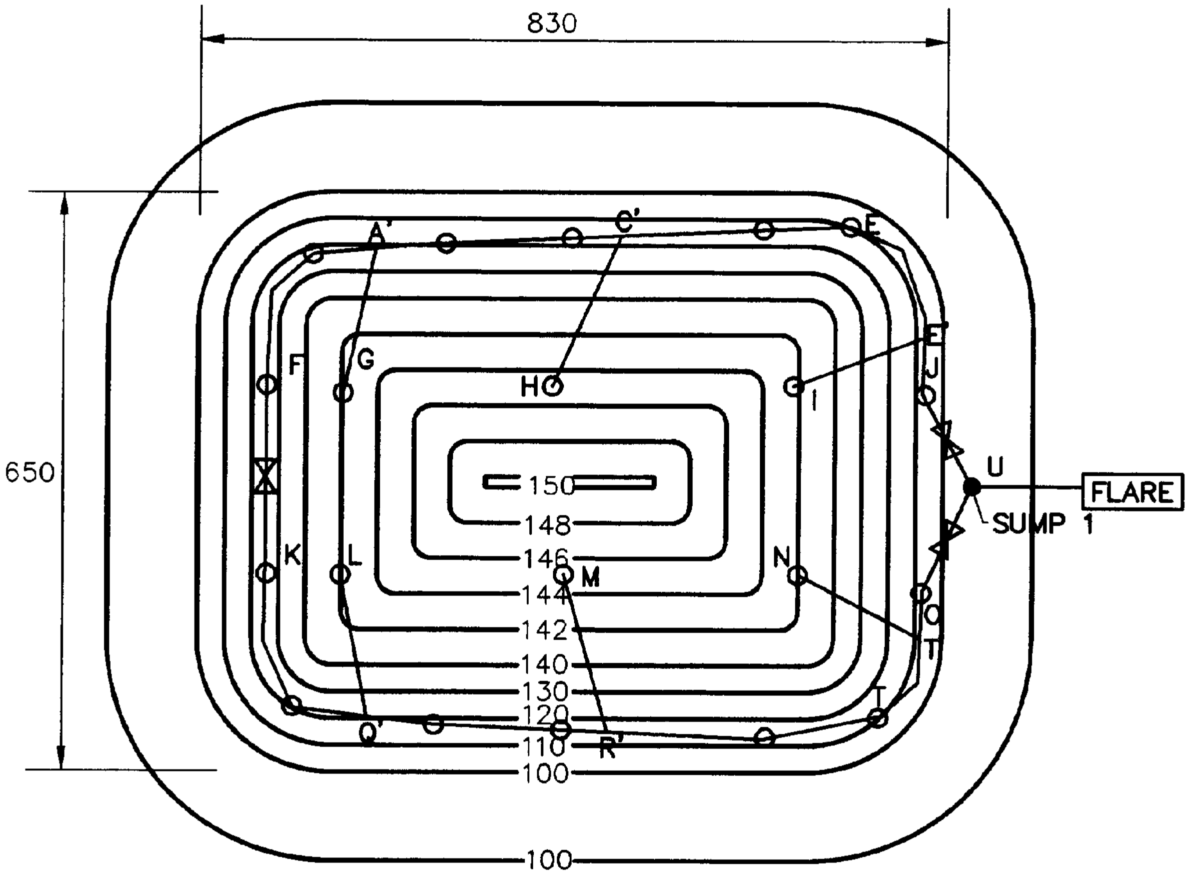


FIGURE E-5

MODEL LANDFILL LATERAL STATEMENT
H-C' HEADER SECTION REFERENCED IN CALCULATIONS

LEGEND

○ GAS EXTRACTION WELL

● SUMP

— GAS LATERAL

⋈ IN-LINE ISOLATION VALVE/
MONITORING STATION

8. Condensate Generation Rate

Assumptions:

- Landfill gas is saturated with moisture
- Landfill gas parameters as noted above
- Climatological data for the site indicates an average ambient air temperature of 55 ^{0}F
- Landfill gas density is sufficiently similar to air to use psychometric charts developed for air saturated with water
- Landfill gas condensate density is sufficiently similar to water to use psychometric charts developed for air saturated with water

Methodology:

- Determine humidity and specific volume for air saturated with water for each temperatures ranging from the assumed average ambient temperature to the maximum system temperature
- Calculate the concentration of water (condensate) entrained in the air (gas)
- Calculate the volume of water (condensate) extracted per unit time for the design gas flow rate
- Determine the maximum volume of water (condensate) produced per unit time as averaged for the year

Calculations:

Calculations for the Model Landfill - Condensate Generation can be found on the following page.

Lateral header statement used for the calculations is illustrated in Figure E-5.

MODEL LANDFILL

CONDENSATE GENERATION CALCULATIONS

Assume:
173 cfm
100 % relative humidity
55 degrees F in piping
density of condensate = density of water

Calculations:

1. Water Concentration (# water/cu ft wet air) = Humidity (# water/# dry air)/Specific Volume (cu ft wet air/# dry air)
2. Volume of Water Extracted (gallons/day) = # water/cu ft wet air * flowrate (cfm) * 1440 (minutes/day) * 0.12 (gallons/#)
3. Volume of Water Condensed (gallons/day) = Volume of Water Extracted at X degrees - Volume of Water Extracted at 55 degrees.

Temperature	Humidity	Spec. Vol.	1. Water Concentration	2. Volume of Water Extracted, gallons/day	3. Volume of WaterCondensed, gallons/day
55	0.0093	13.17	7.06e-04	21.11	0
60	0.01108	13.329	8.31e-04	24.85	3.74
65	0.01326	13.504	9.82e-04	29.35	8.24
70	0.01581	13.688	1.16e-03	34.53	13.42
75	0.01881	13.882	1.36e-03	40.51	19.40
80	0.02231	14.088	1.58e-03	47.34	26.23
85	0.02639	14.309	1.84e-03	55.13	34.02
90	0.03115	14.547	2.14e-03	64.01	42.90
95	0.03668	14.804	2.48e-03	74.07	52.96
100	0.04312	15.083	2.86e-03	85.46	64.35
105	0.05061	15.389	3.29e-03	98.31	77.20
110	0.05932	15.725	3.77e-03	112.77	91.66