

# Chapter 5

## Gas Emission Analysis and Collection System Design

### 5.1 Introduction

This chapter provides information on select topics related to cover system gas emission analysis and collection system design. The specific topics discussed in this chapter are:

- mechanisms of gas generation and emission (Section 5.2);
- characteristics of selected gas emissions models (Section 5.3); and
- design of gas collection systems (Section 5.4).

### 5.2 Mechanisms of Gas Generation and Emissions

#### 5.2.1 Overview

Landfill gas emissions result from the anaerobic decomposition of organic material in landfills. Landfill gas emissions have been found to be a concern to human health and the environment due to the explosive potential of the gas, emissions of hazardous air pollutants (HAPs) and volatile organic compounds (VOC), emissions of methane that contribute to climate change, and odor nuisance associated with landfill gas. Landfills emit more than 100 nonmethane organic compounds (NMOCs) (EPA 1997 a and b). The majority of NMOCs are VOCs which contribute to urban smog. Over thirty of the landfill gas NMOCs are classified as HAPs (EPA 1997 a and b). As a result, landfills are listed as a source as part of the Urban Air Toxic Strategy. EPA has available the Landfill Gas Emissions Model (LandGEM) which estimates landfill gas emissions based on the quantity of waste, waste acceptance rate, and other site specific information. This is based on a first-order decomposition rate equation (Thorneloe, 1999). For older sites or sites where re-use or nearby development is being considered, EPA is producing guidance for evaluating the subsurface vapor intrusion to indoor air pathway (Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils.) This guidance is based on gathering site-specific data, which can be used in LandGEM or for characterizing landfill gas emissions using field test measurements. Updates and additional information regarding this guidance can be found at <http://www.epa.gov/epaoswer/hazwaste/ca/eis/vapor.htm>. The rate of gas emissions through the cover systems of MSW landfills and CERCLA sites is dependent on the gas generation rate, whether the facility has a liner system, site hydrogeology, characteristics of the cover system, and characteristics of any gas control system. The Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils provides assistance in determining the need and extent of gas control.

Gas emissions from MSW landfills are governed by the RCRA Subtitle D regulations, which address the personal safety and fire/explosion hazards of landfill gas, and the Clean Air Act (CAA) regulations, which regulate emissions of non-methane organic compounds (NMOCs) as a surrogate to total landfill gas emissions, which include VOC, HAPs, and methane. The CAA

regulations require landfill gas collection and control at landfills that (1) contain at least 2.5 million megagrams (Mg) or 2.5 million cubic meters of waste and (2) emit 50 Mg per year or more of NMOCs (EPA, 1998). EPA's emission guidelines (EGs) apply to existing landfills that were in operation from November 8, 1987 to May 30, 1991. EPA's new source and performance standards (NSPS) apply to any existing landfill constructed on or after May 30, 1991 or which undergo changes in design capacities on or after May 30, 1991. To help evaluate performance of the gas collection and control system, the NSPS/EGs (60 CFR §753) require that:

*“Each owner or operator of a MSW landfill gas collection and control system used to comply with the provisions of Sec. 60.752(b)(2)(ii) of this subpart shall...(d) Operate the collection system so that the methane concentration is less than 500 parts per million above background at the surface of the landfill. To determine if this level is exceeded, the owner or operator shall conduct surface testing around the perimeter of the collection area along a pattern that traverses the landfill at 30 meter intervals and where visual observations indicate elevated concentrations of landfill gas, such as distressed vegetation and cracks or seeps in the cover....”*

For further information on the requirements of these regulations and available technical documents and fact sheets, refer to <http://www.epa.gov/ttnatw01/landfill/landflpg.html> .

The Agency believes that modern hazardous waste landfills and waste piles will not typically be a significant source of gas or volatile emissions. The promulgation of EPA's Land Disposal Restrictions significantly decreased the potential for emissions of organics from these facilities as compared to older facilities, and the requirement of a GM barrier component (see Section 1.2.2) further limits uncontrolled emissions from these facilities. There are no regulatory requirements regarding emissions from hazardous waste landfills and waste piles. In contrast, older hazardous waste facilities and some CERCLA sites that were closed with a cover system containing only soil materials may have the potential to emit gas or organic vapors and may need evaluation.

Emission of particulates from waste containment facilities and remediation sites is also a concern for the Agency. However, this type of emission is not addressed in this guidance document.

## **5.2.2 MSW Landfill Gas Generation**

MSW contains a significant amount of biodegradable material. Anaerobic decomposition of this material is the primary source of landfill gas. Gas production rates vary with the composition and age of waste, waste volume, waste moisture content, and other factors. The gases produced in a MSW landfill are generated over a relatively long period of time, especially for landfills at arid sites. To help estimate landfill gas emissions, the Agency released software based on a first-order decomposition equation. The software is referred to as the Landfill Gas Generation Model (LandGEM), which has various sets of defaults. One set is for those sites where the CAA requirements are determined to be applicable and appropriate. The other set is typically used for emission inventories and is less conservative than the CAA defaults. Site-specific data can also be used if available.

The anaerobic decomposition of MSW produces two principal gases, methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>), and much smaller quantities of other gases, including nitrogen, oxygen, sulfides, ammonia, and other constituents, and trace amounts of a variety of NMOCs, typically including vinyl chloride, ethylbenzene, toluene, and benzene (Tchobanoglous, 1993; EPA, 1997a, 1997b). The typical constituents found in MSW landfill gas and their concentrations are listed in Table 5-1. Though it is not included in Table 5-1, landfill gas is also typically saturated with water vapor at levels of 1 to 5% by volume. Typical concentrations of NMOCs in landfill gas are presented in Table 5-2.

The escape of landfill gas from a facility can be a significant threat to human health and the environment. The methane in MSW landfill gas can occur in enclosed or confined spaces (typically near the perimeter of the landfill, but in some cases at considerable distances from the perimeter) in concentrations that are odorous, asphyxiating, toxic, corrosive, flammable, or even explosive. Besides methane, other gas constituents, such as hydrogen gas, are also explosive, and certain gas constituents, such as hydrogen sulfide gas, are also toxic at a certain concentrations. Landfills have been identified as the source of nearly 30 HAPs, including the constituents listed in Table 5-2. A more comprehensive list of the different NMOCs and HAPs in landfill gas are contained in EPA's AP-42 which provides guidance for estimating landfill gas emissions (EPA 1997a and b). The source of these HAPs is primarily household and small quantity generator hazardous wastes, including paints, solvents, pesticides, and adhesives.

Because of the hazards posed by MSW landfill gas, care must be taken in handling the gas. CAA regulations establish requirements for MSW landfill gas collection and control at certain facilities, as described in Section 1.4.

**Table 5-1. Typical landfill gas constituents (from Tchobanoglous et al., 1993).**

<b>Constituent</b>	<b>Percent by Volume</b>
Methane	40-60
Carbon dioxide	40-60
Nitrogen	2-5
Oxygen	0.1-1
Ammonia	0.1-1
Sulfides, disulfides, mercaptans, etc.	0-0.2
Hydrogen	0-0.2
Carbon monoxide	0-0.2
Trace constituents	0.01-0.6

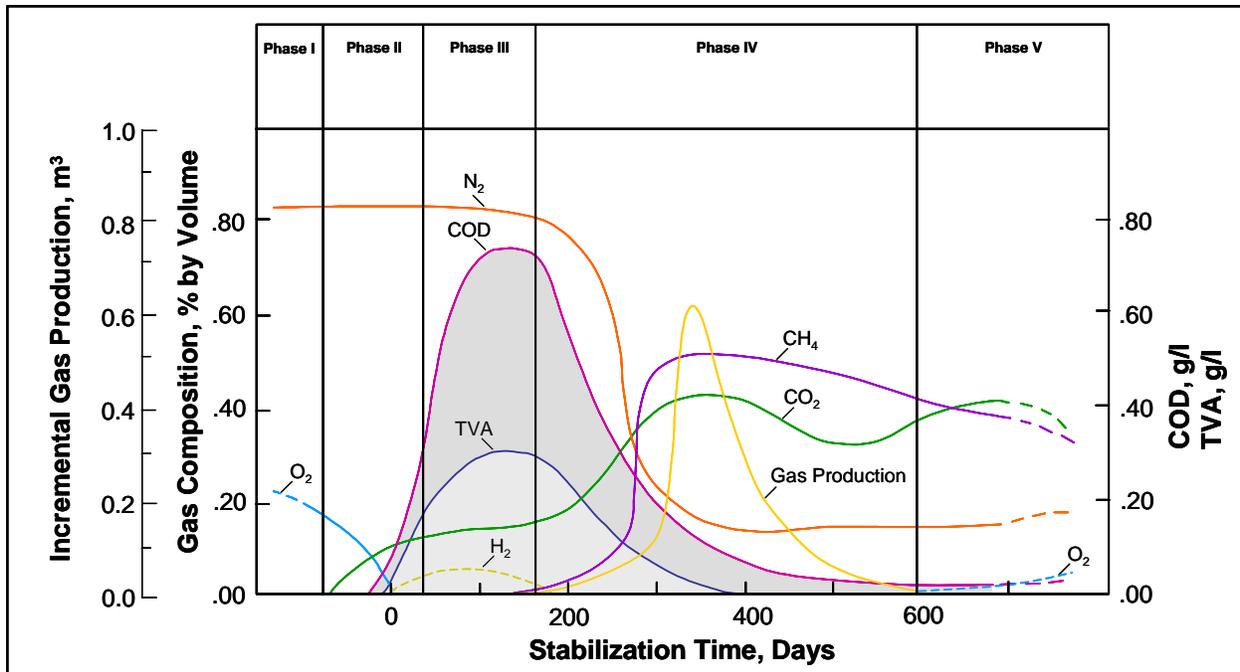
**Table 5-2. Typical concentrations of NMOCs in gas from 25 landfills in southern California (from Pierce et al., 1998).**

Trace Gas Constituent	Average Constituent Concentrations (ppm by volume)	
	Range	Mean
Benzene	0.432-21.8	2.76
Chlorobenzene	0.054-5.24	0.606
1,1-Dichloroethane	0.10-15.9	2.39
1,2-Dichloroethane	0.01-3.74	0.29
Methylene Chloride	0.10-56.3	10.5
Tetrachloroethene	0.30-28.2	3.24
Tetrachloromethane	0.001-0.413	0.046
Toluene	8.37-67.7	28.3
1,1,1-Trichloroethane	0.012-8.28	0.715
Trichloroethene	0.293-13.6	1.60
Vinyl Chloride	0.277-16.8	1.99

Landfill gas generation is often considered to occur in five sequential phases, as shown in Figure 5-1. During Phase I, the initial adjustment phase, waste placement starts, and the waste begins to accumulate moisture. Microbes in the waste begin to acclimatize to the landfill environment. With plenty of substrate and nutrients available, aerobic microbes start to degrade the waste, producing water, carbon dioxide, organic acids, and inorganic minerals. The aerobic decomposition is sustained by the oxygen trapped within the waste mass. Because Phase I is relatively short lived and involves aerobic decomposition, it is sometimes combined with Phase II and referred to as the "aerobic phase".

During Phase II, the transition phase, oxygen trapped within the landfill is depleted and the landfill transitions from an aerobic to anaerobic environment. Since the amount of trapped oxygen is limited, this stage is also relatively short lived (i.e., a few days to a few months). As oxygen is depleted, a trend for reducing conditions is established, with a shifting of electron acceptors from oxygen to nitrates and sulfates. Reduction of these latter molecules, often produces nitrogen gas and hydrogen sulfide gas. In addition, the carbon dioxide level begins to increase, causing the formation of carbonic acid and a decrease in the leachate pH to the acidic range. Waste temperatures are hottest during this phase, reaching 54 to 71°C.

In Phase III, the acid phase, waste is degraded anaerobically. The waste first undergoes hydrolysis, where larger organic molecules are converted into shorter, soluble molecules and hydrogen gas is produced. Acidogenic bacteria then convert the hydrolyzed compounds into volatile organic acids (VOAs). The acids, in turn, cause the pH to drop (e.g., to 5.5 to 6.5) in



**Figure 5-1. Generalized Phases in the Generation of Landfill Gases (modified from Kreith, 1994).**

turn causing heavy metals concentrations to rise in the leachate. Viable biomass growth associated with the acidogenic bacteria and the rapid consumption of substrate and nutrients are the predominant features of this phase. The primary gas formed during this stage is carbon dioxide.

In Phase IV, the methane fermentation phase, the VOAs and hydrogen gas produced by the acidogens are converted into methane by methanogenic bacteria. Both acid production and methane fermentation occur during this phase; however, methane fermentation predominates. The highest landfill gas generation rates occur during this phase. As the VOAs are utilized, the pH of the leachate increases to more neutral values (e.g., 6.8 to 8) and heavy metals concentrations decrease. Sulfates and nitrates are reduced to sulfides and ammonia. Gas temperatures have dropped by this phase to about 38 to 54°C. Gas production probably begins to drop off at the lower end of this temperature range. As described by Hutric and Soni (1997), a study of an experimental MSW digester showed that gas generation rates peaked at two temperatures: about 40 °C, when mesophilic bacteria are present, and between 55 and 60°C, when thermophilic bacteria are present. At temperatures below 40 °C, gas generation rates decrease rapidly with decreasing temperature.

By Phase V, the maturation phase, the landfill has matured and the readily biodegradable material has been stabilized (i.e., converted to methane or carbon dioxide). Biodegradation is limited by lack of readily degradable substrate and nutrients, so biological activity slows. The landfill gas production rate, consequently, also decreases. Both carbon dioxide and methane

gases are produced, but at much lower rates than in Phase IV. Towards the latter part of this phase, the landfill may become aerobic, with oxidizing conditions, and small amounts of oxygen and nitrogen gases may be present.

Since landfills are heterogeneous and all waste is not placed at the same time, the stages described above typically occur concurrently in different areas and depths of an active or recently closed landfill. The dichotomy between stages is often masked when a landfill is active and new waste is being added to old. After a landfill closes, the landfill tends to move into Phase IV, with the newer waste just keeping the landfill at this phase for a longer time period.

The rate of waste degradation is controlled by the amount and type of degradable materials in the waste, waste temperature, waste moisture content, and other factors. Food waste may degrade about five times faster than yard waste, fifteen times faster than paper, and fifty times faster than wood or leather. Degradation is enhanced (the reaction rates increase) by the initial temperature increase caused by the heat released from aerobic degradation. The temperature falls over time, however, as the waste loses heat to its surroundings. In deeper landfills, this heat is better retained and degradation occurs faster than in shallower landfills. Water is generated in the aerobic biodegradation process and required for the anaerobic biodegradation process. In addition, water movement through a landfill helps to mix the enzymes, bacteria, and substrate. The subsistence moisture level required by methanogenic bacteria is very low. This is why gas generation occurs even in the driest of landfills (McBean et al., 1995).

Although moisture content is thought to be an important factor in landfill gas emissions, there is much variability in the level of emissions from site to site. Typically, emissions in more arid regions are thought to occur over a longer period of time than sites in more temperate climates. For those sites operated as a wet landfill where leachate has been added or there are other liquid additions, emissions occur over a much faster rate and there can be a high level of fugitive gas emissions depending upon how liquid is added to the site.

### **5.2.3 Gas Emissions**

Water and gas flows occur simultaneously in a waste containment facility or contamination source area as a dynamically-coupled process. As described by Berglund (1998), flow of gas and water within a landfill can be conceptualized as a trickle bed. The liquid phase trickles over the waste particles and the gas phase migrates in the remaining pore space. At the present, it is not possible to effectively integrate all the biochemical reaction and multi-phase transport mechanisms into one model. Instead, the processes must be uncoupled and discussed separately. These processes are: (i) percolation of water through a cover system, which was discussed in Chapter 4; (ii) waste degradation and gas production, which was discussed in Section 5.2.2; and (iii) gas emissions through a cover system, which is discussed in this section.

Gas flow within and through the cover system of a waste containment facility or remediation site is mainly pressure driven at gas pressures above about 3kPa, but also responds to temperature, density, and concentration gradients. Pressures generated by MSW gas may be on the order of 2.5 to 7.5 kPa for younger landfills located in temperate climates to 0.5 kPa for older landfills located in arid climates. As gas pressures increase in a waste mass, the gas travels along the path

of least resistance. The final disposition of the generated gas depends on the engineered controls (e.g., containment systems, gas management system). Gas may be stored in the waste, migrate through a liner or barrier (if they exist) and into available air space in the surrounding subsurface, emitted through the cover into the atmosphere, or collected and treated by a gas management system, if one exists.

Gas emissions may be affected by the gas pressures within a landfill, barometric pressure, moisture content and gas permeability of the soil components of the cover system, chemical diffusion rate through a GM barrier component of the cover system, advective flow rate through any holes in the GM barrier component, and other factors. Barometric pressure is a function of atmospheric pressure and changes in weather. It responds diurnally to atmospheric tides with a high in the early morning hours and a low in the afternoon hours. It also responds to changes in the high and low-pressure systems related to weather conditions. Because gas emissions are typically pressure driven (i.e., convection rather than diffusion is typically the primary transport mechanism), gas emissions generally follow the reverse trend of barometric pressures, due to the effect on pressure gradients. When barometric pressures are highest, gas emissions are lowest and vice versa. For landfills with active gas collection systems, a change in barometric pressure should have less impact on gas emissions than occurs for landfills without these systems. Even if landfill gases move from the landfill, through the cover system, and into the atmosphere, some of the gases may be consumed by microbes in cover system soils. For example, relatively high methane oxidation rates of 45 g/m<sup>2</sup>/d were observed in topsoil above a landfill in California (Whalen et al, 1990); methane concentrations in the air immediately above the topsoil were very low. Oxidation of methane by soil microbes has been demonstrated in controlled laboratory experiments (Knightley et al., 1995). The experiments showed that as the flux of methane into a soil layer decreased, a greater proportion of methane was oxidized. Bogner et al. (1997) report that some investigations of methane oxidation in landfill soil covers have shown essentially all methane to be oxidized in the soil and no release of methane from the landfill. Clearly, however, widespread documentation of atmospheric methane emissions from soil-covered landfills shows that microbial methane degradation in cover soils is often not complete.

With respect to soils, the pores of the soil must be nearly saturated to prevent gas migration. Thus, it is not surprising that landfill gas is often detected at the surface of the soil cover systems. Landfill methane emissions measured at landfill sites and reported in the literature have ranged from about 0.003 to 3,000 g/m<sup>2</sup>/d (Bogner and Scott, 1997). In general, the higher rates were associated with landfills that did not have gas recovery and that were covered with relatively more permeable and/or drier soils. For example, at the Olinda MSW Landfill in Southern California, which is covered by a sandy silt soil layer, measured emission rates were greater than 1,000 g/m<sup>2</sup>/d prior to installation of a gas collection system. After a gas collection system was installed, measured gas flux rates were less than 10 g/m<sup>2</sup>/d. The flux rates were still lower (less than 0.01 g/m<sup>2</sup>/d) in the area of the landfill with a gas recovery system and covered with a clayey silt layer.

## 5.3 Characteristics of Selected Gas Emission Models

### 5.3.1 LandGEM Model for MSW

Gas emission rates for MSW landfills are difficult to predict. They are sometimes estimated as a fraction of calculated gas generation rates or from field data (see Section 8.4). This section presents a method for estimating gas emission rates using the EPA LandGEM computer model. LandGEM calculates landfill gas generation rates. In the model, the gas emission rate is assumed to be equal to the gas generation rate. The model does not account for gas storage within the waste mass, nor subsurface gas migration, which for old unlined landfills can be a significant migration pathway. It is noted that measured gas flow rates are typically lower than the gas generation rates calculated using LandGEM. Gas emissions during operation have been estimated to be 10 to 60% of the total gas generated (Augenstein et al., 1997). However, collection efficiency is never precisely known and, if used in the gas generation equation, must be an assumed value, Hutric and Soni (1997).

The most common method of calculating landfill gas production rates, and the method recommended by EPA (1998), involves using a first-order decomposition rate equation:

$$Q_M = \sum_{i=1}^n 2kL_0M_i(e^{-kt_i}) \quad (\text{Eq. 5-1})$$

where:  $Q_M$  = maximum expected gas generation flow rate, assumed to be comprised of 50% methane and 50% carbon dioxide (Mg/yr);  $k$  = methane generation rate constant ( $\text{yr}^{-1}$ );  $L_0$  = methane generation potential ( $\text{m}^3/\text{Mg}$ );  $M_i$  = mass of solid waste in the  $i^{\text{th}}$  section (Mg); and  $t_i$  = age of the  $i^{\text{th}}$  section (yr). The volume or mass of waste disposed of in the landfill each year is input into the model, and the model uses default parameters or site-specific input parameters to estimate the annual generation of landfill gas and specific gas constituents.

The methane generation rate constant,  $k$ , is a function of waste moisture content, pH, and temperature, and nutrient availability to methanogens. In a study by EPA, the value of  $k$  for MSW landfills was estimated to range from 0.003 to 0.21/yr (EPA, 1998) based on field test data and the results of theoretical models using field test data. For landfills at arid and semi-arid sites (defined by EPA as sites with less than 640 mm of precipitation per year), EPA's "best estimate" of  $k$  is 0.02/yr (EPA, 1997a). The methane generation potential,  $L_0$ , is a function of waste composition. EPA found values for  $L_0$  ranging from 6.2 to 270  $\text{m}^3/\text{Mg}$  based on theoretical modeling and field test data for a number of landfills (EPA, 1998). EPA's "best estimate" of this parameter is 100  $\text{m}^3/\text{Mg}$  (EPA, 1997a). Murphy (1998) indicated that the gas generation rates predicted with the EPA model showed reasonable correspondence to field data from landfills in arid settings when the default parameters were changed to  $k = 0.005/\text{yr}$  and  $L_0 = 16 \text{ m}^3/\text{Mg}$ . For most landfills, the EPA parameters can be used with the EPA model to develop initial estimates of gas generation rates. These parameters can then be adjusted as data on gas flow rates or emissions are collected over time. Hutric and Soni (1997) describe how this data fitting may be carried out.

From chemical analysis of landfill gas samples collected at landfills, EPA also developed “best estimates” of NMOCs and air pollutants for landfills with and without co-disposal of hazardous waste. EPA's best estimate of the NMOC concentration as hexane is 2,420 ppmv for landfills that did not have co-disposal of hazardous waste (EPA, 1998). The measured NMOC concentration reported for the 23 landfill considered by EPA ranged from 240 to 14,300 ppmv (EPA, 1998). As described by Repa (1994), at the sites in the EPA study, the compounds most frequently detected in landfill gas included benzene, tetrachloroethene, toluene, trichlorofluoromethane, trichloroethane, and vinyl chloride. The compounds detected at the highest average concentration included ethylbenzene, methylene chloride, propane, and xylenes.

### **5.3.2 Diffusion Model for Emissions of Organic Vapors**

For hazardous waste landfills and waste piles, if any volatiles are left in the waste when it reaches the facilities, they are rapidly emitted from the surface of exposed waste. After a cover system is placed over the waste, emissions of organic vapors occur by diffusion, convection by barometric pumping, and gas venting.

The model EPA has used for hazardous waste landfills and waste piles assumes diffusion of volatiles from the waste surface through the cover system (and neglects convective flow due to changes in barometric pressure) (EPA, 1992). Volatiles in the waste are assumed to be in equilibrium with air in void spaces of the waste. When the organic vapors reach the surface of the cover system, they are assumed to be removed by wind (i.e., the constituent concentration at the cover system surface is assumed to be zero).

## **5.4 Design of Gas Collection Systems**

Gas collection systems are typically designed as part of passive gas management systems or active gas extraction systems utilizing negative pressure systems. Passive systems are primarily effective at controlling convective flow (due to pressure and density gradients) and have limited success controlling diffusive flow. Active systems are effective in controlling both types of flow. Active systems are preferred when a significant amount of gas is being generated, and these systems are required for facilities of certain sizes to reduce the amount of gas constituents released to the atmosphere. Design of gas collection systems can be based on calculated gas generation rates or vapor emission rates or from the results of field tests (e.g., pump tests).

Some design engineers collect and vent or extract MSW landfill gas with vertical, perforated collection wells (typically 1 to 3 wells per hectare) without a continuous gas collection layer beneath the hydraulic barrier component of the cover system. This approach can be justified if the waste itself is sufficiently permeable to gas, if the gas wells are relatively closely spaced, or, at arid sites, where gas is generated relatively slowly. With gas wells, the gas moves within the waste to the perforations in the pipe and then flows or is drawn out of the system. Another approach to venting or extracting gas from a landfill involves installing a continuous gas collection layer beneath the cover system barrier. With this type of system, shallow gas venting or extraction pipes will tie into the gas collection layer. Gas collection trenches with periodic vent or extraction pipes represents a third approach to gas collection beneath the cover system. Also, a combination of these three gas venting/extraction systems can be used. For active

systems, additional components may include a vacuum blower system, a manifold to connect multiple wells, off-gas treatment (e.g., enclosed flare, gas-to-energy system, carbon adsorption), condensate holding tank, and monitoring and control equipment.

In any case (deep wells penetrating the waste, a continuous gas collection layer, beneath the barrier layer, and/or collection trenches) the system outlets are typically plastic pipes extending up through the cover system. Gas flow through the pipes can be either passive (vented to the atmosphere or flared) or active (collected through a header using a blower system to create a small vacuum). Without a gas management system, gas pressure will build up in the landfill. Note that with a GM in the cover system and relatively small cover soil thicknesses, gas pressure can cause GM uplift. Even if the GM is not physically lifted, positive gas pressure beneath the GM can lower the effective stress at the interface between the GM and underlying material (e.g., GCL), thereby reducing interface shear strength and potentially contributing to a slope failure. At several landfill facilities, this latter effect had led to slippage of the GM and overlying cover materials (Bonaparte et al., 2002) creating high tensile stresses as evidenced by compression ridges in the cover soil and folding of the GM at the slope toe and tension cracks in the cover soil near the slope crest.

Based on the above, all of the three types of gas collection systems require careful design considerations:

- if gas removal is by deep wells, the uppermost pipe perforations should be effective in capturing gas in the upper layers of waste;
- if gas removal is by a gas collection layer beneath the GM and vents, the gas collection layer should be designed with adequate long-term transmissivity; and
- if gas is removed by horizontal collection trenches, some of the trenches should be placed in close proximity to the bottom of the cover system to prevent gas accumulation and uplift pressure on the cover system GM.

In general, gas collection systems should be designed with a minimal number of penetrations through the cover system, as each penetration is a potential location for preferential flow (i.e., short-circuiting of gas through the cover system).

For passive systems, a maximum of one well per acre should be included initially (EPA, 1991). If monitoring of the vents reveals excessively high gas concentrations, then additional wells can be installed.

In addition to the above, as gases are collected, condensate usually forms because the temperature at the surface is often less than the temperature of the gas. Gas collection systems often include condensate traps and piping that directs condensate to some collection point (e.g., back into a MSW landfill).