CHAPTER 2
Investigations

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

- Size and depth of the landfill.
- Nature of the waste and the potential for producing methane and other gases.
- Age of the waste.
- Type of cover and liner present.
- Existing gas collection and monitoring systems.
- Hydrogeologic conditions surrounding the landfill.
- Location and number of adjacent buildings.

2.1.1. *General.* After preliminary information has been gathered, a decision needs to be made about how much additional information needs to be gathered in order to estimate the amount of gas being generated and whether or not the gas is migrating off-site. The following paragraphs describe methods of site characterization, quantifying landfill gas production, and the potential for off-site migration.

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

2.1.3. *Hydrogeologic Conditions.* The migration of landfill gas off-site is greatly affected by the geologic conditions at the site. High permeability materials such as sands, gravels, and fractured or weathered bedrock transmit vapors very effectively. Low permeability layers such as silts and clays have smaller pore sizes and do not transmit gas vapors as readily. These zones also tend to retain more moisture due to capillary forces and this poses an additional barrier to vapor flow. High permeability layers in contact with landfills are capable of transmitting gases over large distances, especially when they are overlain by a continuous layer of low permeability material.

Hydrogeologic investigations must be performed to determine the geologic conditions, ground water table elevation, and potential paths for LFG to escape. EM 1110-1-1804 Geotechnical Investigations and EM 1110-1-4000 Monitor Well Design, Installation, and Documentation at Hazardous and/or Toxic Waste Sites provides general information on performing field investigations and well installation. The Table 2-1 lists important parameters that should be determined when investigating the off-site migration of landfill gas.

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

Parameter	Collection Method	Reference
Stratigraphy	Soil borings	EM 1110-1-1804 ASTM D 2487 ASTM D 2488
Depth to ground water	Monitoring wells	EM 1110-1-4000
Heterogeneity/utility trenches	Geophysical investigations	EM 1110-1-1804
Moisture content	Soil borings	ASTM D 2216
Grain size/porosity	Soil borings	ASTM D 422
Atterberg limits	Soil borings	ASTM D 4318
Soil gas concentration	Gas monitoring probes	EM 1110-1-4001
Soil gas surveys	Gas monitoring probes	EM 1110-1-4001

2.1.4. *Ambient Air Quality*. Ambient air quality monitoring may be necessary to help determine the need for a landfill gas collection system. A typical monitoring program would include the collection of air samples at pre-determined locations based on meteorological conditions at the site over an appropriate time period (8 hours, 24 hours, etc.). Ambient conditions including temperature, barometric pressure and precipitation events should be recorded. Gaseous parameters analyzed may include CH_4, H_2S, and NMOCs. Additional information regarding modeling and monitoring air quality for landfill emission sources can be found in EP 1110-1-21, Air Pathway Analysis for the Design of HTRW Remedial Action Projects.

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

2.1.6. *Monitoring Gases in Structures*. Basements and crawl spaces of buildings located near landfills are potential collection points for methane and other gases. Methane that collects in these confined spaces can create a potential explosion hazard. Basements and crawl spaces of buildings located in the vicinity of landfills should be monitored for landfill gas during the investigative phase.

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

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

2.1.7.1. *Sampling Depths.* Soil gas concentrations diminish near the landfill surface due to diffusion into the atmosphere and advective exchange of air from the atmosphere. Generally, more concentrated vapors are found at depth, although concentrations vary significantly due to proximity to sources and preferred lateral migration pathways. Landfill gas samples for characterization of gas composition and design of landfill gas collection and treatment systems should be taken at least 3 feet below the surface. In many cases, obstructions will prevent penetration of the sampling probe to the required depth and offset sampling locations will be required. Deeper sampling depths are appropriate where the waste layer is thick. When sampling for landfill gas migration, the depth of the sampling probe/well may be dictated by regulation, but should consider the depth of preferred migration pathways, based on the stratigraphy at the site, and the nature of potential exposure such as basements or manmade features.

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

2.1.7.3. *Sampling Methods.* There are two primary means to collect subsurface vapor samples; active soil gas sampling and passive (non-pumping, sorbent) sampling. In addition, surface flux measurements can also be made. The following paragraphs describe each to these methods.

2.1.7.3.1. *Active Soil Gas Sampling.* Active soil gas sampling requires that samples of the actual soil gas filling the pore spaces in the subsurface be collected and analyzed. This method is most appropriate for gathering data on concentrations for off-gas treatment system design, for determination of risk posed by the landfill gas or for quantifying gas migration to receptors. These samples represent a snapshot of the soil gas concentrations and are, therefore, susceptible to variations due to changes in barometric pressure, gas generation rates, and precipitation events. Sampling requires placement (either temporary or permanent) of a probe or well into the subsurface. This can be accomplished by direct-push methods (e.g., cone penetrometer) or a drill rig. Drilling into a landfill requires additional safety precautions and in accordance with EM 385-1-1, a hazard task analysis for the work should be completed prior to drilling. In some cases, slide hammers or similar devices can be used if the material into which the probe is to be placed poses little resistance. Typically, decontaminated steel pipe/probes are used for temporary sampling probes, although steel drive tips connected to teflon tubing can be used, as can driven casing (e.g., using sonic or dual-tube casing hammer rigs - packers are placed in the casing to reduce the volume of air needed to be removed). Permanent probes are often installed in a manner similar to ground water monitoring wells and can be constructed of steel or PVC. Well seals that prevent atmospheric air entry are critical. Refer to EM 1110-1-4001, Soil Vapor Extraction and Bioventing, Chapter 5, for more information on well/probe construction. Once installed, the probe or well is sampled by drawing a vacuum on the well using a vacuum pump and purging the well of several well volumes of gas. Typically, 3-5 times the well volume is purged. Monitoring of vapor concentrations as purging progresses can indicate the ideal amount of purging, however, 3 volumes is typically a minimum. Actual sampling depends on the required container for the sample. Summa canisters can be used directly and are the proper choice for off-site analysis, but glass gas-tight syringes or tedlar bags can be used for on-site analysis. Care must be taken to avoid leakage of atmospheric air into the sample container during placement or removal of the sample container to/from the air stream. Refer to ASTM D5314 for more information on proper sampling methods. Upon completion of sampling, temporary probes are typically removed. The hole should then be sealed with grout or bentonite. Unnecessary permanent probes should be decommissioned in accordance with state regulation. Refer to EM 1110-1-4000, Monitoring Well Design, Installation, and Documentation at HTRW Sites for additional information on well decommissioning requirements.

2.1.7.3.2. *Passive Soil Gas Sampling.* Passive soil gas sampling techniques allow the sorption of the soil gas vapors onto activated carbon or similar material over some period of time. The sorbent material is later collected and submitted for thermal desorption and analysis. These methods do not allow the quantification of the soil gas concentrations unless gas flow is directed and measured through the sorptive cartridge or filter. This technique is most appropriate for qualitatively identifying the locations of contaminant sources or composition of the soil gas. These techniques allow a longer exposure to the soil gas and are therefore less susceptible to variations due to barometric pressure changes, gas generation rates, and precipitation events. Different vendors have different materials and placement methods. In some cases, the sorbent material is enclosed in an inverted glass vial or moisture resistant fabric and buried at depth in the soil for later retrieval. Other vendors have materials that are set under a stainless steel cover at the ground surface. The materials are placed and left for some period of time (typically days to weeks) before retrieval. Proper retrieval requires the filling of any holes created as part of the survey.

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

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

2.1.9. *Analytical Methods.* The determination of the appropriate analytical methods is very project specific and depends on the project objectives, data quality objectives, and nature and concentration of contaminants of interest. The project chemist must be consulted to assure appropriate methods are chosen. Analysis can be conducted in the field using portable equipment or in a fixed lab. EM 200-1-3 "Requirements for the Preparation of Sampling and Plans" provides guidance on selecting the most appropriate type of sampling approach, i.e., the number of samples that should be collected from each medium, and the laboratory analyses that should be performed to achieve the objectives of the sampling program with the desired level of confidence.

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

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

2.1.9.2. *Fixed Laboratory Analyses.* For definitive analyses, samples are sent to off-site labs and analyzed according to specified methods. Summa canisters are typically used to assure representative samples arrive at the lab. A chemist should be consulted for proper selection and coordination with an off-site lab. The methods typically specified have quality control requirements, and the use of a quality assurance lab provides a measure of the adequacy of the primary lab. Additional information on test methods for air samples can be found in EPA/625/R-96/010b Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air. This document describes Method TO-14A which is a procedure for sampling and analysis of volatile organic compounds (VOCs) in ambient air. The method was originally based on collection of whole air samples in summa passivated stainless steel canisters, but has now been generalized to other specially prepared canisters.

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

2.2. **Estimation of LFG Emissions.** LFG emissions are site-specific and are a function of both controllable and uncontrollable factors. It is, therefore, difficult to accurately predict the rate of LFG emission from a landfill. A summary table of reported methane generation rates is provided in Table 3-1. One approach to predicting gas generation from a municipal solid waste landfill is to employ a simplified model that is consistent with fundamental principles. Several models are available for estimating the LFG generation rate using site-specific input parameters. The LandGEM model is one of these models and was developed by the US Environmental Protection Agency to estimate landfill gas emissions and to determine regulatory applicability to CAA requirements. There are other LFG emission models in use by industry that also work very well. The Clean Air Act regulations allow states the opportunity to use the results from models other than LandGEM. However, most of these models are proprietary and are not as readily available as LandGEM. Regardless of what model is used, the accuracy of the inputs drives the results and given the level of uncertainty, it makes estimating landfill emissions very difficult.

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

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

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

2.2.1.2. Defaults for k and Lo are suggested although site-specific values can be developed through field test measurements and then used in the software to develop more accurate estimates. The program is designed to model and store multiple landfill studies. Within a landfill study, reports and graphs of the estimated emissions can be produced for any particular pollutant including NMOCs (total and speciated), methane, and carbon dioxide.

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

2.2.1.4. The software is being used by landfill owners and operators to determine if a landfill is subject to the control requirements of the New Source Performance Standard (NSPS) for new MSW landfills (40 CFR 60 Subpart WWW) or the emission guidelines (EG) for existing MSW landfills (40 CFR 60 Subpart Cc). The NSPS and EG were initially proposed May 30, 1991 (EPA, 1991b), and the final rule was promulgated on March 12, 1996 (EPA, 1996a). LandGEM is also being used to develop estimates for State emission inventories. Given the intended use of the software, there are two sets of defaults.

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

$$M_{\mathrm{NMOC}} = 2kL_{\mathrm{o}} \sum_{i=1}^{n} M_{\mathrm{i}} (e^{-kti})(C_{\mathrm{NMOC}})(3.6 \times 10^{-9})$$

where:

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

The mass of nondegradable solid waste may be subtracted from the total mass of solid waste in a particular section of the landfill when calculating the value for M_i.

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

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

where:

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

The value of L_0 is most directly proportional to the waste's cellulose content. The theoretical CH_4 generation rate increases as the cellulose content of the refuse increases. If the landfill conditions are not favorable to methanogenic activity, there would be a reduction in the theoretical value of L_0. This implies that the theoretical (potential) value of CH_4 generation may never be obtained. The obtainable value of L_0 for the refuse (or specific waste components) can be estimated by performing biodegradability tests on the waste under conditions of temperature, moisture, nutrient content, and pH likely to exist in the landfill. Theoretical and obtainable L_0 values have been reported in literature to range from approximately 6 to 270 m^3 CH_4 per metric ton of waste for municipal landfills.

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

$C_aH_bO_cN_dS_e$ ---> $vCH_4 + wCO_2 + xN_2 + yNH_3 + zH_2S$ + humus

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

2.2.3. *Regression Model.* The EPA Air and Energy Engineering Research Laboratory (AEERL) began a research program in 1990 with the goal of improving global landfill methane emission estimates. Part of this program was a field study to gather information that was used to develop an empirical model of methane emissions. Twenty-one US landfills with gas recovery systems were included in the study. Site-specific information included average methane recovery rate, landfill size, refuse mass, average age of the refuse, and climate. A correlation analysis showed that refuse mass was positively linearly correlated with landfill depth, volume, area, and well depth. Regression analysis of the methane recovery rate on depth, refuse mass, and volume was significant, but depth was the best predictive variable ($R^2 = 0.53$). Refuse mass was nearly as good ($R^2 = .5$). None of the climate variables (precipitation, average temperature, dew point) correlated well with the methane recovery rate. Much of the variability in methane recovery remains unexplained, and is likely due to between-site differences in landfill construction, operation, and refuse composition. A model for global landfill emissions estimation was proposed based on this data. A simple model correlating refuse mass to methane recovery with a zero intercept was developed:

$$Q_{CH4} = 4.52\ W$$

where:

Q_{CH4} = CH_4 flow rate (m^3/min)
W = mass of refuse (Mg)

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