## 2.4 Landfills

### 2.4.1 General[1-4]

A municipal solid waste (MSW) landfill unit is a discrete area of land or an excavation that receives household waste, and that is not a land application unit, surface impoundment, injection well, or waste pile. An MSW landfill unit may also receive other types of wastes, such as commercial solid waste, nonhazardous sludge, and industrial solid waste. The municipal solid waste types potentially accepted by MSW landfills include:

- MSW,
- Household hazardous waste,
- Municipal sludge,
- Municipal waste combustion ash,
- Infectious waste,
- Waste tires,
- Industrial nonhazardous waste,
- Conditionally exempt small quantity generator (CESQG) hazardous waste,
- Construction and demolition waste,
- Agricultural wastes,
- Oil and gas wastes, and
- Mining wastes.

Municipal solid waste management in the United States is dominated by disposal in landfills. Approximately 67 percent of solid waste is landfilled, 16 percent is incinerated, and 17 percent is recycled or composted. There were an estimated 5,345 active MSW landfills in the United States in 1992. In 1990, active landfills were receiving an estimated 118 million megagrams (Mg) (130 million tons) of waste annually, with 55 to 60 percent reported as household waste, and 35 to 45 percent reported as commercial waste.

### 2.4.2 Process Description[2,5]

There are three major designs for municipal landfills. These are the area, trench, and ramp methods. All of these methods utilize a three step process, which includes spreading the waste, compacting the waste, and covering the waste with soil. The trench and ramp methods are not commonly used, and are not the preferred methods when liners and leachate collection systems are utilized or required by law. The area fill method involves placing waste on the ground surface or landfill liner, spreading it in layers, and compacting with heavy equipment. A daily soil cover is spread over the compacted waste. The trench method entails excavating trenches designed to receive a day's worth of waste. The soil from the excavation is often used for cover material and wind breaks. The ramp method is typically employed on sloping land, where waste is spread and compacted similar to the area method; however, the cover material obtained is generally from the front of the working face of the filling operation.

Modern landfill design often incorporates liners constructed of soil (e. g., recompacted clay), or synthetics (e. g., high density polyethylene), or both to provide an impermeable barrier to leachate (i. e., water that has passed through the landfill) and gas migration from the landfill.

### 2.4.3 Control Technology[1,2,6]

The Resource Conservation and Recovery Act (RCRA) Subtitle D regulations promulgated on October 9, 1991, require that the concentration of methane generated by MSW landfills not exceed 25 percent of the lower explosive limit (LEL) in on-site structures, such as scale houses, or the LEL at the facility property boundary.

Proposed New Source Performance Standards (NSPS) and emission guidelines for air emissions from MSW landfills for certain new and existing landfills were published in the Federal Register on May 30, 1991. The regulation, if adopted, will require that Best Demonstrated Technology (BDT) be used to reduce MSW landfill emissions from affected new and existing MSW landfills emitting greater than or equal to 150 Mg/yr (165 tons/yr) of non-methanogenic organic compounds (NMOCs). The MSW landfills that would be affected by the proposed NSPS would be each new MSW landfill, and each existing MSW landfill that has accepted waste since November 8, 1987, or that has capacity available for future use. Control systems would require: (1) a well-designed and well-operated gas collection system, and (2) a control device capable of reducing NMOCs in the collected gas by 98 weight-percent.

Landfill gas collection systems are either active or passive systems. Active collection systems provide a pressure gradient in order to extract landfill gas by use of mechanical blowers or compressors. Passive systems allow the natural pressure gradient created by the increase in landfill pressure from landfill gas generation to mobilize the gas for collection.

Landfill gas control and treatment options include (1) combustion of the landfill gas, and (2) purification of the landfill gas. Combustion techniques include techniques that do not recover energy (i. e., flares and thermal incinerators), and techniques that recover energy (i. e., gas turbines and internal combustion engines) and generate electricity from the combustion of the landfill gas. Boilers can also be employed to recover energy from landfill gas in the form of steam. Flares involve an open combustion process that requires oxygen for combustion, and can be open or enclosed. Thermal incinerators heat an organic chemical to a high enough temperature in the presence of sufficient oxygen to oxidize the chemical to carbon dioxide ($CO_2$) and water. Purification techniques can also be used to process raw landfill gas to pipeline quality natural gas by using adsorption, absorption, and membranes.

### 2.4.4 Emissions[2,7]

Methane ($CH_4$) and $CO_2$ are the primary constituents of landfill gas, and are produced by microorganisms within the landfill under anaerobic conditions. Transformations of $CH_4$ and $CO_2$ are mediated by microbial populations that are adapted to the cycling of materials in anaerobic environments. Landfill gas generation, including rate and composition, proceeds through four phases. The first phase is aerobic (e. g., with oxygen [$O_2$] available) and the primary gas produced is $CO_2$. The second phase is characterized by $O_2$ depletion, resulting in an anaerobic environment, where large amounts of $CO_2$ and some hydrogen ($H_2$) are produced. In the third phase, $CH_4$ production begins, with an accompanying reduction in the amount of $CO_2$ produced. Nitrogen ($N_2$) content is initially high in landfill gas in the first phase, and declines sharply as the landfill proceeds through the second and third phases. In the fourth phase, gas production of $CH_4$, $CO_2$, and $N_2$ becomes fairly steady. The total time and phase duration of gas generation varies with landfill conditions (e. g., waste composition, design management, and anaerobic state).

The rate of emissions from a landfill is governed by gas production and transport mechanisms. Production mechanisms involve the production of the emission constituent in its vapor phase through vaporization, biological decomposition, or chemical reaction. Transport mechanisms involve the transportation of a volatile constituent in its vapor phase to the surface of the landfill, through the air

boundary layer above the landfill, and into the atmosphere. The three major transport mechanisms that enable transport of a volatile constituent in its vapor phase are diffusion, convection, and displacement.

2.4.4.1 Uncontrolled Emissions -

To estimate uncontrolled emissions of the various compounds present in landfill gas, total landfill gas emissions must first be estimated. Uncontrolled $CH_4$ emissions may be estimated for individual landfills by using a theoretical first-order kinetic model of methane production developed by the EPA.[2] This model is known as the Landfill Air Emissions Estimation model, and can be accessed from the EPA's Control Technology Center bulletin board. The Landfill Air Emissions Estimation model equation is as follows:

$$Q_{CH4} = L_o \ R \ (e^{-kc} - e^{-kt}) \qquad (1)$$

where:

$Q_{CH4}$ = Methane generation rate at time t, $m^3/yr$;
$L_o$ = Methane generation potential, $m^3$ $CH_4/Mg$ refuse;
R = Average annual refuse acceptance rate during active life, Mg/yr;
e = Base log, unitless;
k = Methane generation rate constant, $yr^{-1}$;
c = Time since landfill closure, yrs (c = 0 for active landfills); and
t = Time since the initial refuse placement, yrs.

Site-specific landfill information is generally available for variables R, c, and t. When refuse acceptance rate information is scant or unknown, R can be determined by dividing the refuse in place by the age of the landfill. Also, nondegradable refuse should be subtracted from the mass of acceptance rate to prevent overestimation of $CH_4$ generation. The average annual acceptance rate should only be estimated by this method when there is inadequate information available on the actual average acceptance rate.

Values for variables $L_o$ and k must be estimated. Estimation of the potential $CH_4$ generation capacity of refuse ($L_o$) is generally treated as a function of the moisture and organic content of the refuse. Estimation of the $CH_4$ generation constant (k) is a function of a variety of factors, including moisture, pH, temperature, and other environmental factors, and landfill operating conditions. Specific $CH_4$ generation constants can be computed by use of the EPA Method 2E.

The Landfill Air Emission Estimation model uses the proposed regulatory default values for $L_o$ and k. However, the defaults were developed for regulatory compliance purposes. As a result, it contains conservative $L_o$ and k default values in order to protect human health, to encompass a wide range of landfills, and to encourage the use of site-specific data. Therefore, different $L_o$ and k values may be appropriate in estimating landfill emissions for particular landfills and for use in an emissions inventory.

A k value of 0.04/yr is appropriate for areas with normal or above normal precipitation rather than the default value of 0.02/yr. For landfills with drier waste, a k value of 0.02/yr is more appropriate. An $L_o$ value of 125 $m^3/Mg$ (4,411 $ft^3/Mg$) refuse is appropriate for most landfills. It should be emphasized that in order to comply with the NSPS, the model defaults for k and $L_o$ must be applied as specified in the final rule.

Landfill gas consists of approximately 50 percent by volume $CO_2$, 50 percent $CH_4$, and trace amounts of NMOCs when gas generation reaches steady state conditions. Therefore, the estimate derived for $CH_4$ generation using the Landfill Air Emissions Estimation model can also be used to represent $CO_2$ generation. Addition of the $CH_4$ and $CO_2$ emissions will yield an estimate of total landfill gas emissions.

If site-specific information is available to suggest that the $CH_4$ content of landfill gas is not 50 percent, then the site-specific information should be used, and the $CO_2$ emission estimate should be adjusted accordingly.

Emissions of NMOCs result from NMOCs contained in the landfilled waste, and from their creation from biological processes and chemical reactions within the landfill cell. The Landfill Air Emissions Estimation model contains a proposed regulatory default value for total NMOCs of 8000 ppmv, expressed as hexane. However, there is a wide range for total NMOC values from landfills. The proposed regulatory default value for NMOC concentration was developed for regulatory compliance and to provide the most cost-effective default values on a national basis. For emissions inventory purposes, it would be preferable that site-specific information be taken into account when determining the total NMOC concentration. A value of 4,400 ppmv as hexane is preferable for landfills known to have co-disposal of MSW and commercial/industrial organic wastes. If the landfill is known to contain only MSW or have very little organic commercial/industrial wastes, then a total NMOC value of 1,170 ppmv as hexane should be used.

If a site-specific total NMOC concentration is available (i. e., as measured by EPA Reference Method 25C), it must be corrected for air infiltration into the collected landfill gas before it can be combined with the estimated landfill gas emissions to estimate total NMOC emissions. The total NMOC concentration is adjusted for air infiltration by assuming that $CO_2$ and $CH_4$ are the primary (100 percent) constituents of landfill gas, and the following equation is used:

$$\frac{C_{NMOC}(\text{ppmv as hexane})\ (1 \times 10^6)}{C_{CO_2}\ (\text{ppmv}) + C_{CH_4}\ (\text{ppmv})} = \begin{matrix} C_{NMOC}\ \text{ppmv as hexane} \\ (\text{corrected for air infiltration}) \end{matrix} \quad (2)$$

where:

$C_{NMOC}$ = Total NMOC concentration in landfill gas, ppmv as hexane;
$C_{CO_2}$ = $CO_2$ concentration in landfill gas, ppmv;
$C_{CH_4}$ = $CH_4$ Concentration in landfill gas, ppmv; and
$1 \times 10^6$ = Constant used to correct NMOC concentration to units of ppmv.

Values for $C_{CO_2}$ and $C_{CH_4}$ can be usually be found in the source test report for the particular landfill along with the total NMOC concentration data.

To estimate total NMOC emissions, the following equation should be used:

$$Q_{NMOC} = 2\ Q_{CH_4} * C_{NMOC}/(1 \times 10^6) \quad (3)$$

where:

$Q_{NMOC}$ = NMOC emission rate, $m^3$/yr;
$Q_{CH_4}$ = $CH_4$ generation rate, $m^3$/yr (from the Landfill Air Emissions Estimation model);
$C_{NMOC}$ = Total NMOC concentration in landfill gas, ppmv as hexane; and
2 = Multiplication factor (assumes that approximately 50 percent of landfill gas is $CH_4$).

The mass emissions per year of total NMOCs (as hexane) can be estimated by the following equation:

$$M_{NMOC} = Q_{NMOC} * \left[\frac{1050.2}{(273 + T)}\right] \quad (4)$$

where:

$M_{NMOC}$ = NMOC (total) mass emissions (kg/yr);
$Q_{NMOC}$ = NMOC emission rate ($m^3$/yr); and
T = Temperature of landfill gas ($^oC$).

This equation assumes that the operating pressure of the system is approximately 1 atmosphere, and represents total NMOCs, based on the molecular weight of hexane. If the temperature of the landfill gas is not known, a temperature of 25°C (75°F) is recommended.

Uncontrolled emission concentrations of individual NMOCs along with some inorganic compounds are presented in Table 2.4-1. These individual NMOC and inorganic concentrations have already been corrected for air infiltration and can be used as input parameters in the Landfill Air Emission Estimation model for estimating individual NMOC emissions from landfills when site-specific data are not available. An analysis of the data based on the co-disposal history (with hazardous wastes) of the individual landfills from which the concentration data were derived indicates that for benzene and toluene, there is a difference in the uncontrolled concentration. Table 2.4-2 presents the corrected concentrations for benzene and toluene to use based on the site's co-disposal history.

Similar to the estimation of total NMOC emissions, individual NMOC emissions can be estimated by the following equation:

$$Q_{NMOC} = 2\ Q_{CH_4} * C_{NMOC}/(1 \times 10^6) \quad (5)$$

where:

$Q_{NMOC}$ = NMOC emission rate, $m^3$/yr;
$QCH_4$ = $CH_4$ generation rate, $m^3$/yr (from the Landfill Air Emission Estimation model);
$C_{NMOC}$ = NMOC concentration in landfill gas, ppmv; and
2 = Multiplication factor (assumes that approximately 50 percent of landfill gas is $CH_4$).

The mass emissions per year of each individual landfill gas compound can be estimated by the following equation:

$$I_{NMOC} = Q_{NMOC} * \frac{\text{(Molecular weight of compound)}}{(8.205 \times 10^{-5}\ m^3\text{-atm/mol-}^oK)\ (1000\ g)\ (273 + T)} \quad (6)$$

where:

$I_{NMOC}$ = Individual NMOC mass emissions (kg/yr);
$Q_{NMOC}$ = NMOC emission rate ($m^3$/yr); and
T = Temperature of landfill gas ($^oC$).

Table 2.4-1. UNCONTROLLED LANDFILL GAS CONCENTRATIONS[a]

| Compound | Molecular Weight | Median ppmv | EMISSION FACTOR RATING |
|---|---|---|---|
| 1,1,1-Trichloroethane (methyl chloroform)* | 133.42 | 0.27 | B |
| 1,1,2,2-Tetrachloroethane* | 167.85 | 0.20 | C |
| 1,1,2-Trichloroethane* | 133.42 | 0.10 | E |
| 1,1-Dichloroethane (ethylidene dichloride)* | 98.95 | 2.07 | B |
| 1,1-Dichloroethene (vinylidene chloride)* | 96.94 | 0.22 | B |
| 1,2-Dichloroethane (ethylene dichloride)* | 98.96 | 0.79 | B |
| 1,2-Dichloropropane (propylene dichloride)* | 112.98 | 0.17 | C |
| Acetone | 58.08 | 6.89 | B |
| Acrylonitrile* | 53.06 | 7.56 | D |
| Bromodichloromethane | 163.87 | 2.06 | C |
| Butane | 58.12 | 3.83 | B |
| Carbon disulfide* | 76.13 | 1.00 | E |
| Carbon monoxide | 28.01 | 309.32 | C |
| Carbon tetrachloride* | 153.84 | 0.00 | B |
| Carbonyl sulfide* | 60.07 | 24.00 | E |
| Chlorobenzene* | 112.56 | 0.20 | D |
| Chlorodiflouromethane | 67.47 | 1.22 | B |
| Chloroethane (ethyl chloride)* | 64.52 | 1.17 | B |
| Chloroform* | 119.39 | 0.27 | B |
| Chloromethane | 50.49 | 1.14 | B |
| Dichlorodifluoromethane | 120.91 | 12.17 | B |
| Dichlorofluoromethane | 102.92 | 4.37 | C |
| Dichloromethane (methylene chloride)* | 84.94 | 14.30 | C |
| Dimethyl sulfide (methyl sulfide) | 62.13 | 76.16 | B |
| Ethane | 30.07 | 227.65 | D |
| Ethyl mercaptan (ethanethiol) | 62.13 | 0.86 | C |
| Ethyl benzene* | 106.16 | 4.49 | B |
| Fluorotrichloromethane | 137.38 | 0.73 | B |
| Hexane* | 86.17 | 6.64 | B |
| Hydrogen sulfide | 34.08 | 36.51 | B |
| Methyl ethyl ketone* | 72.10 | 6.13 | B |
| Methyl isobutyl ketone* | 100.16 | 1.22 | B |
| Methyl mercaptan | 48.10 | 10.43 | B |
| NMOC (as hexane) | 86.17 | 1170 | D |
| Pentane | 72.15 | 3.32 | B |
| Perchloroethylene (tetrachloroethylene)* | 165.83 | 3.44 | B |

Table 2.4-1 (cont.).

| Compound | Molecular Weight | Median ppmv | EMISSION FACTOR RATING |
|---|---|---|---|
| Propane | 44.09 | 10.60 | B |
| Trichloroethylene* | 131.40 | 2.08 | B |
| t-1,2-Dichloroethene | 96.94 | 4.01 | B |
| Vinyl chloride* | 62.50 | 7.37 | B |
| Xylene* | 106.16 | 12.25 | B |

[a] References 9-35. Source Classification Code 5-02-006-02. * = Hazardous air pollutants listed in the *Clean Air Act*.

Table 2.4-2. UNCONTROLLED CONCENTRATIONS OF BENZENE AND TOLUENE BASED ON HAZARDOUS WASTE DISPOSAL HISTORY[a]

| Compound | Molecular Weight | Concentration ppmv | EMISSION FACTOR RATING |
|---|---|---|---|
| Benzene* | 78.11 | | |
| Co-disposal | | 24.99 | D |
| Unknown | | 2.25 | B |
| No co-disposal | | 0.37 | D |
| Toluene* | 92.13 | | |
| Co-disposal | | 102.62 | D |
| Unknown | | 31.63 | B |
| No co-disposal | | 8.93 | D |

[a] References 9-35. Source Classification Code 5-02-006-02. * = Hazardous air pollutants listed in the *Clean Air Act*.

2.4.4.2 Controlled Emissions -

Emissions from landfills are typically controlled by installing a gas collection system, and destroying the collected gas through the use of internal combustion engines, flares, or turbines. Gas collection systems are not 100 percent efficient in collecting landfill gas, so emissions of $CH_4$ and NMOCs at a landfill with a gas recovery system still occur. To estimate controlled emissions of $CH_4$, NMOCs, and other constituents in landfill gas, the collection efficiency of the system must first be estimated. Reported collection efficiencies typically range from 60 to 85 percent, with an average of 75 percent most commonly assumed. If site-specific collection efficiencies are available, they should be used instead of the 75 percent average.

Uncollected $CH_4$, $CO_2$, and NMOCs can be calculated with the following equation:

$$1 - \frac{\text{Collection Efficiency}}{100} \quad (7)$$

Controlled emission estimates also need to take into account the control efficiency of the control device. Control efficiencies of $CH_4$ and NMOCs with differing control devices are presented in Table 2.4-3. Emissions from the control devices need to be added to the uncollected emissions to estimate total controlled emissions.

Emission factors for secondary compounds ($CO_2$, CO, and $NO_x$) exiting the control device are presented in Tables 2.4-4 and 2.4-5.

The reader is referred to Sections 13.2-2 (Unpaved Roads, SCC 5-01-004-01), and Section 13.2.3 (Heavy Construction Operations) of Volume I, and Section II-7 (Heavy-duty Construction Equipment) of Volume II, of the AP-42 document for determination of associated dust and exhaust emissions from these emission sources at MSW landfills.

Table 2.4-3. CONTROL EFFICIENCIES FOR LANDFILL GAS CONSTITUENTS[a]

| Control Device | Compound | Average Control Efficiency | EMISSION FACTOR RATING |
|---|---|---|---|
| IC Engine (no SCC) | Benzene* | 83.83 | E |
| | Trichloroethylene* | 89.60 | E |
| | Perchloroethylene* | 89.41 | E |
| | NMOCs (as hexane*) | 79.75 | E |
| | 1,1,1-Trichloroethane* | 92.47 | E |
| | Chloroform* | 99.00 | E |
| | Toluene* | 79.71 | E |
| | Carbon tetrachloride* | 98.50 | E |
| Turbine (no SCC) | Perchloroethylene* | 99.97 | E |
| | Toluene* | 99.91 | E |
| | 1,1,1-Trichloroethane* | 95.18 | E |
| | Trichloroethylene* | 99.92 | E |
| | Vinyl chloride* | 98.00 | E |
| Flare (5-02-006-01) (5-03-006-01) | Chloroform* | 93.04 | D |
| | Perchloroethylene* | 85.02 | C |
| | Toluene* | 93.55 | C |
| | Xylene* | 99.28 | E |
| | 1,1,1-Trichloroethane* | 85.24 | C |
| | 1,2-Dichloroethane* | 88.68 | E |
| | Benzene* | 89.50 | C |
| | Carbon tetrachloride* | 95.05 | D |
| | Methylene chloride* | 97.60 | E |
| | NMOCs (as hexane*) | 83.16 | E |
| | Trichloroethylene* | 96.20 | C |
| | t-1,2-Dichloroethene* | 99.59 | E |
| | Vinyl chloride* | 97.61 | C |

[a] References 9-35. Source Classification Codes in parentheses. * = Hazardous air pollutant listed in the *Clean Air Act*.

Table 2.4-4 (Metric Units). EMISSION RATES FOR SECONDARY COMPOUNDS EXITING CONTROL DEVICES[a]

| Control Device | Compound | Average Rate, kg/hr/dscmm Uncontrolled Methane | EMISSION FACTOR RATING |
|---|---|---|---|
| Flare | Carbon dioxide | 85.7[b] | B |
| (5-02-006-01) | Carbon monoxide | 0.80 | B |
| (5-03-006-01) | Nitrogen dioxide | 0.11 | C |
| | Methane | 1.60 | C |
| | Sulfur dioxide | 0.03 | E |
| IC Engine | Carbon dioxide | 85.7[b] | B |
| (no SCC) | Nitrogen dioxide | 0.80 | E |
| Turbine | Carbon dioxide | 85.7[b] | B |
| (no SCC) | Carbon monoxide | 0.32 | E |

[a] Source Classification Codes in parentheses.
[b] Carbon dioxide emission factors are based on a mass balance on the combustion of a 50/50 mixture of methane and $CO_2$.

Table 2.4-5 (English Units). EMISSION RATES FOR SECONDARY COMPOUNDS EXITING CONTROL DEVICES[a]

| Control Device | Compound | Average Rate, lb/hr/dscfm Uncontrolled Methane | EMISSION FACTOR RATING |
|---|---|---|---|
| Flare | Carbon dioxide | 5.3[b] | B |
| (5-02-006-01) | Carbon monoxide | 0.050 | B |
| (5-03-006-01) | Nitrogen dioxide | 0.007 | C |
| | Methane | 0.105 | C |
| | Sulfur dioxide | 0.002 | E |
| IC Engine | Carbon dioxide | 5.3[b] | B |
| (no SCC) | Nitrogen dioxide | 0.050 | E |
| Turbine | Carbon dioxide | 5.3[b] | B |
| (no SCC) | Carbon monoxide | 0.021 | E |

[a] Source Classification Codes in parentheses.
[b] Carbon dixoide emission factors are based on a mass balance on the combustion of a 50/50 mixture of methane and $CO_2$.

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