CHAPTER

2

Landfill Gas Basics

This chapter provides basic information about landfill gas—what it is composed of, how it is produced, and the conditions that affect its production. It also provides information about how landfill gas moves and travels away from the landfill site. Finally, the chapter presents an overview of the types of landfills that might be present in your community and the regulatory requirements that apply to each.

What is landfill gas composed of?

Landfill gas is composed of a mixture of hundreds of different gases. By volume, landfill gas typically contains 45% to 60% methane and 40% to 60% carbon dioxide. Landfill gas also includes small amounts of nitrogen, oxygen, ammonia, sulfides, hydrogen, carbon monoxide, and nonmethane organic compounds (NMOCs) such as trichloroethylene, benzene, and vinyl chloride. Table 2-1 lists "typical" landfill gases, their percent by volume, and their characteristics.

How is landfill gas produced?

Three processes—bacterial decomposition, volatilization, and chemical reactions—form landfill gas.

- ***Bacterial decomposition.*** Most landfill gas is produced by bacterial decomposition, which occurs when organic waste is broken down by bacteria naturally present in the waste and in the soil used to cover the landfill. Organic wastes include food, garden waste, street sweepings, textiles, and wood and paper products. Bacteria decompose organic waste in four phases, and the composition of the gas changes during each phase. The box on page 5 provides detailed information about the four phases of bacterial decomposition and the gases produced during each phase. Figure 2-1 shows gas production at each of the four stages.
- ***Volatilization.*** Landfill gases can be created when certain wastes, particularly organic compounds, change from a liquid or a solid into a vapor. This process is known as volatilization. NMOCs in landfill gas may be the result of volatilization of certain chemicals disposed of in the landfill.
- ***Chemical reactions.*** Landfill gas, including NMOCs, can be created by the reactions of certain chemicals present in waste. For example, if chlorine bleach and ammonia come into contact with each other within the landfill, a harmful gas is produced.

Table 2-1: Typical Landfill Gas Components

Component	Percent by Volume	Characteristics
methane	45–60	Methane is a naturally occurring gas. It is colorless and odorless. Landfills are the single largest source of U.S. man-made methane emissions.
carbon dioxide	40–60	Carbon dioxide is naturally found at small concentrations in the atmosphere (0.03%). It is colorless, odorless, and slightly acidic.
nitrogen	2–5	Nitrogen comprises approximately 79% of the atmosphere. It is odorless, tasteless, and colorless.
oxygen	0.1–1	Oxygen comprises approximately 21% of the atmosphere. It is odorless, tasteless, and colorless.
ammonia	0.1–1	Ammonia is a colorless gas with a pungent odor.
NMOCs (non-methane organic compounds)	0.01–0.6	NMOCs are organic compounds (i.e., compounds that contain carbon). (Methane is an organic compound but is not considered an NMOC.) NMOCs may occur naturally or be formed by synthetic chemical processes. NMOCs most commonly found in landfills include acrylonitrile, benzene, 1,1-dichloroethane, 1,2-cis dichloroethylene, dichloromethane, carbonyl sulfide, ethylbenzene, hexane, methyl ethyl ketone, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride, and xylenes.
sulfides	0–1	Sulfides (e.g., hydrogen sulfide, dimethyl sulfide, mercaptans) are naturally occurring gases that give the landfill gas mixture its rotten-egg smell. Sulfides can cause unpleasant odors even at very low concentrations.
hydrogen	0–0.2	Hydrogen is an odorless, colorless gas.
carbon monoxide	0–0.2	Carbon monoxide is an odorless, colorless gas.

Source: Tchobanoglous, Theisen, and Vigil 1993; EPA 1995

The Four Phases of Bacterial Decomposition of Landfill Waste

Bacteria decompose landfill waste in four phases. The composition of the gas produced changes with each of the four phases of decomposition. Landfills often accept waste over a 20- to 30-year period, so waste in a landfill may be undergoing several phases of decomposition at once. This means that older waste in one area might be in a different phase of decomposition than more recently buried waste in another area.

Phase I

During the first phase of decomposition, aerobic bacteria—bacteria that live only in the presence of oxygen—consume oxygen while breaking down the long molecular chains of complex carbohydrates, proteins, and lipids that comprise organic waste. The primary byproduct of this process is carbon dioxide. Nitrogen content is high at the beginning of this phase, but declines as the landfill moves through the four phases. Phase I continues until available oxygen is depleted. Phase I decomposition can last for days or months, depending on how much oxygen is present when the waste is disposed of in the landfill. Oxygen levels will vary according to factors such as how loose or compressed the waste was when it was buried.

Phase II

Phase II decomposition starts after the oxygen in the landfill has been used up. Using an anaerobic process (a process that does not require oxygen), bacteria convert compounds created by aerobic bacteria into acetic, lactic, and formic acids and alcohols such as methanol and ethanol. The landfill becomes highly acidic. As the acids mix with the moisture present in the landfill, they cause certain nutrients to dissolve, making nitrogen and phosphorus available to the increasingly diverse species of bacteria in the landfill. The gaseous byproducts of these processes are carbon dioxide and hydrogen. If the landfill is disturbed or if oxygen is somehow introduced into the landfill, microbial processes will return to Phase I.

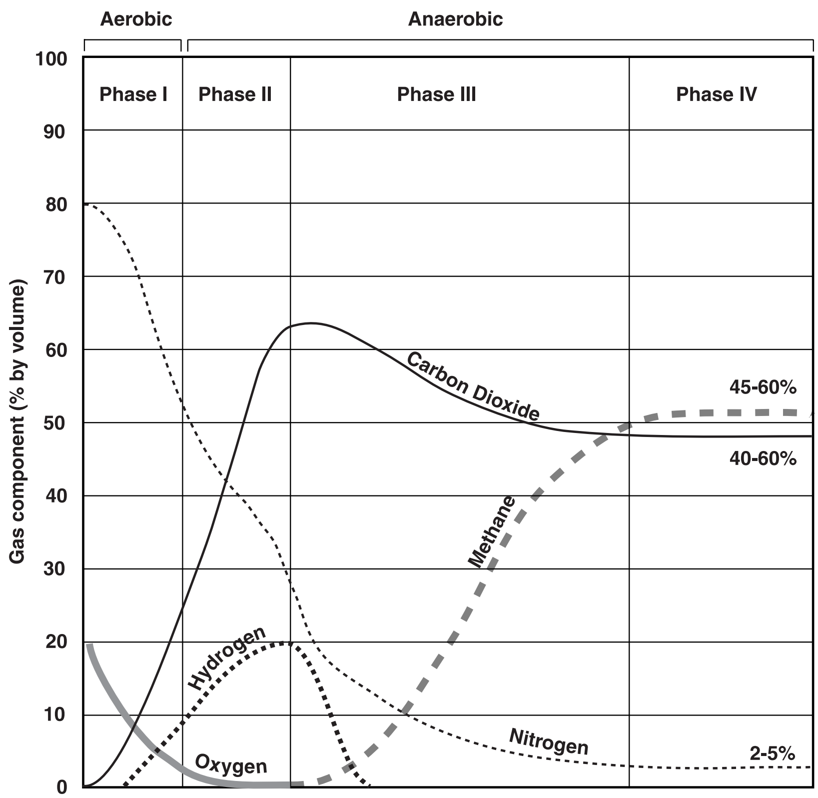
Phase III

Phase III decomposition starts when certain kinds of anaerobic bacteria consume the organic acids produced in Phase II and form acetate, an organic acid. This process causes the landfill to become a more neutral environment in which methane-producing bacteria begin to establish themselves. Methane- and acid-producing bacteria have a symbiotic, or mutually beneficial, relationship. Acid-producing bacteria create compounds for the methanogenic bacteria to consume. Methanogenic bacteria consume the carbon dioxide and acetate, too much of which would be toxic to the acid-producing bacteria.

Phase IV

Phase IV decomposition begins when both the composition and production rates of landfill gas remain relatively constant. Phase IV landfill gas usually contains approximately 45% to 60% methane by volume, 40% to 60% carbon dioxide, and 2% to 9% other gases, such as sulfides. Gas is produced at a stable rate in Phase IV, typically for about 20 years; however, gas will continue to be emitted for 50 or more years after the waste is placed in the landfill (Crawford and Smith 1985). Gas production might last longer, for example, if greater amounts of organics are present in the waste, such as at a landfill receiving higher than average amounts of domestic animal waste.

Figure 2-1: Production Phases of Typical Landfill Gas



Note: Phase duration time varies with landfill conditions
Source: EPA 1997

What conditions affect landfill gas production?

The rate and volume of landfill gas produced at a specific site depend on the characteristics of the waste (e.g., composition and age of the refuse) and a number of environmental factors (e.g., the presence of oxygen in the landfill, moisture content, and temperature).

- ***Waste composition.*** The more organic waste present in a landfill, the more landfill gas (e.g., carbon dioxide, methane, nitrogen, and hydrogen sulfide) is produced by the bacteria during decomposition. The more chemicals disposed of in the landfill, the more likely NMOCs and other gases will be produced either through volatilization or chemical reactions.
- ***Age of refuse.*** Generally, more recently buried waste (i.e., waste buried less than 10 years) produces more landfill gas through bacterial decomposition, volatilization, and chemical reactions than does older waste (buried more than 10 years). Peak gas production usually occurs from 5 to 7 years after the waste is buried.
- ***Presence of oxygen in the landfill.*** Methane will be produced only when oxygen is no longer present in the landfill.
- ***Moisture content.*** The presence of moisture (unsaturated conditions) in a landfill increases gas production because it encourages bacterial decomposition. Moisture may also promote chemical reactions that produce gases.

- ***Temperature.*** As the landfill's temperature rises, bacterial activity increases, resulting in increased gas production. Increased temperature may also increase rates of volatilization and chemical reactions.

The box on the following page provides more detailed information about how these variables affect the rate and volume of landfill gas production.

How does landfill gas move?

Once gases are produced under the landfill surface, they generally move away from the landfill. Gases tend to expand and fill the available space, so that they move, or "migrate," through the limited pore spaces within the refuse and soils covering of the landfill. The natural tendency of landfill gases that are lighter than air, such as methane, is to move upward, usually through the landfill surface. Upward movement of landfill gas can be inhibited by densely compacted waste or landfill cover material (e.g., by daily soil cover and caps). When upward movement is inhibited, the gas tends to migrate horizontally to other areas within the landfill or to areas outside the landfill, where it can resume its upward path. Basically, the gases follow the path of least resistance. Some gases, such as carbon dioxide, are denser than air and will collect in subsurface areas, such as utility corridors. Three main factors influence the migration of landfill gases: diffusion (concentration), pressure, and permeability.

- ***Diffusion (concentration).*** Diffusion describes a gas's natural tendency to reach a uniform concentration in a given space, whether it is a room or the earth's atmosphere. Gases in a landfill move from areas of high gas concentrations to areas with lower gas concentrations. Because gas concentrations are generally higher in the landfill than in the surrounding areas, landfill gases diffuse out of the landfill to the surrounding areas with lower gas concentrations.
- ***Pressure.*** Gases accumulating in a landfill create areas of high pressure in which gas movement is restricted by compacted refuse or soil covers and areas of low pressure in which gas movement is unrestricted. The variation in pressure throughout the landfill results in gases moving from areas of high pressure to areas of low pressure. Movement of gases from areas of high pressure to areas of lower pressure is known as *convection*. As more gases are generated, the pressure in the landfill increases, usually causing subsurface pressures in the landfill to be higher than either the atmospheric pressure or indoor air pressure. When pressure in the landfill is higher, gases tend to move to ambient or indoor air.
- ***Permeability.*** Gases will also migrate according to where the pathways of least resistance occur. Permeability is a measure of how well gases and liquids flow through connected spaces or pores in refuse and soils. Dry, sandy soils are highly permeable (many connected pore spaces), while moist clay tends to be much less permeable (fewer connected pore spaces). Gases tend to move through areas of high permeability (e.g., areas of sand or gravel) rather than through areas of low permeability (e.g., areas of clay or silt). Landfill covers are often made of low-permeability soils, such as clay. Gases in a covered landfill, therefore, may be more likely to move horizontally than vertically.

Factors Affecting Landfill Gas Production

Waste Composition. The more organic waste present in a landfill, the more landfill gas is produced by bacterial decomposition. Some types of organic waste contain nutrients, such as sodium, potassium, calcium, and magnesium, that help bacteria thrive. When these nutrients are present, landfill gas production increases. Alternatively, some wastes contain compounds that harm bacteria, causing less gas to be produced. For example, methane-producing bacteria can be inhibited when waste has high salt concentrations.

Oxygen in the Landfill. Only when oxygen is used up will bacteria begin to produce methane. The more oxygen present in a landfill, the longer aerobic bacteria can decompose waste in Phase I. If waste is loosely buried or frequently disturbed, more oxygen is available, so that oxygen-dependent bacteria live longer and produce carbon dioxide and water for longer periods. If the waste is highly compacted, however, methane production will begin earlier as the aerobic bacteria are replaced by methane-producing anaerobic bacteria in Phase III. Methane gas starts to be produced by the anaerobic bacteria only when the oxygen in the landfill is used up by the aerobic bacteria; therefore, any oxygen remaining in the landfill will slow methane production. Barometric highs will tend to introduce atmospheric oxygen into surface soils in shallow portions of a landfill, possibly altering bacterial activity. In this scenario, waste in Phase IV, for example, might briefly revert to Phase I until all the oxygen is used up again.

Moisture Content. The presence of a certain amount of water in a landfill increases gas production because moisture encourages bacterial growth and transports nutrients and bacteria to all areas within a landfill. A moisture content of 40% or higher, based on wet weight of waste, promotes maximum gas production (e.g., in a capped landfill). Waste compaction slows gas production because it increases the density of the landfill contents, decreasing the rate at which water can infiltrate the waste. The rate of gas production is higher if heavy rainfall and/or permeable landfill covers introduce additional water into a landfill.

Temperature. Warm temperatures increase bacterial activity, which in turn increases the rate of landfill gas production. Colder temperatures inhibit bacterial activity. Typically, bacterial activity drops off dramatically below 50° Fahrenheit (F). Weather changes have a far greater effect on gas production in shallow landfills. This is because the bacteria are not as insulated against temperature changes as compared to deep landfills where a thick layer of soil covers the waste. A capped landfill usually maintains a stable temperature, maximizing gas production. Bacterial activity releases heat, stabilizing the temperature of a landfill between 77° F and 113° F, although temperatures up to 158° F have been noted. Temperature increases also promote volatilization and chemical reactions. As a general rule, emissions of NMOCs double with every 18° F increase in temperature.

Age of Refuse. More recently buried waste will produce more gas than older waste. Landfills usually produce appreciable amounts of gas within 1 to 3 years. Peak gas production usually occurs 5 to 7 years after wastes are dumped. Almost all gas is produced within 20 years after waste is dumped; however, small quantities of gas may continue to be emitted from a landfill for 50 or more years. A low-methane yield scenario, however, estimates that slowly decomposing waste will produce methane after 5 years and continue emitting gas over a 40-year period. Different portions of the landfill might be in different phases of the decomposition process at the same time, depending on when the waste was originally placed in each area. The amount of organic material in the waste is an important factor in how long gas production lasts.

Sources: Crawford and Smith 1985; DOE 1995; EPA 1993.

What conditions affect landfill gas migration?

The direction, speed, and distance of landfill gas migration depend on a number of factors, described below.

- ***Landfill cover type.*** If the landfill cover consists of relatively permeable material, such as gravel or sand, then gas will likely migrate up through the landfill cover. If the landfill cover consists of silts and clays, it is not very permeable; gas will then tend to migrate horizontally underground. If one area of the landfill is more permeable than the rest, gas will migrate through that area.
- ***Natural and man-made pathways.*** Drains, trenches, and buried utility corridors (such as tunnels and pipelines) can act as conduits for gas movement. The natural geology often provides underground pathways, such as fractured rock, porous soil, and buried stream channels, where the gas can migrate.
- ***Wind speed and direction.*** Landfill gas naturally vented into the air at the landfill surface is carried by the wind. The wind dilutes the gas with fresh air as it moves it to areas beyond the landfill. Wind speed and direction determine the gas's concentration in the air, which can vary greatly from day to day, even hour by hour. In the early morning, for example, winds tend to be gentle and provide the least dilution and dispersion of the gas to other areas.
- ***Moisture.*** Wet surface soil conditions may prevent landfill gas from migrating through the top of the landfill into the air above. Rain and moisture may also seep into the pore spaces in the landfill and "push out" gases in these spaces.
- ***Groundwater levels.*** Gas movement is influenced by variations in the groundwater table. If the water table is rising into an area, it will force the landfill gas upward.
- ***Temperature.*** Increases in temperature stimulate gas particle movement, tending also to increase gas diffusion, so that landfill gas might spread more quickly in warmer conditions. Although the landfill itself generally maintains a stable temperature, freezing and thawing cycles can cause the soil's surface to crack, causing landfill gas to migrate upward or horizontally. Frozen soil over the landfill may provide a physical barrier to upward landfill gas migration, causing the gas to migrate further from the landfill horizontally through soil.
- ***Barometric and soil gas pressure.*** The difference between the soil gas pressure and barometric pressure allows gas to move either vertically or laterally, depending on whether the barometric pressure is higher or lower than the soil gas pressure. When barometric pressure is falling, landfill gas will tend to migrate out of the landfill into surrounding areas. As barometric pressure rises, gas may be retained in the landfill temporarily as new pressure balances are established.

How far can landfill gas travel?

It is difficult to predict the distance that landfill gas will travel because so many factors affect its ability to migrate underground; however, travel distances greater than 1,500 feet have been observed. Computer models that use data about the landfill and surrounding soil conditions can predict the approximate migration patterns from existing landfills. More information about models available for assessing landfill gas is provided in Chapter Four.

> A study conducted by the New York State Department of Health found that of 38 landfills, gas migrated underground up to 1,000 feet at 1 landfill, 500 feet at 4 landfills, and only 250 feet from the landfill boundary at 33 landfills.
>
> —(ATSDR 1998)

How does landfill gas enter buildings and homes?

Gases migrating from a landfill may eventually reach buildings and homes. Foundation cracks and gaps, pressure differences between the inside and outside of the building or home, mechanical ventilation systems, and leakage areas (e.g., utility entry points, construction joints, or floor drain systems) provides entry points for gases. Buildings and houses with basements generally provide the most easy access for gases migrating in the soil. The amount of gases let into a building or home depends on a number of factors, including the construction and maintenance practices. The gas concentration in indoor air also depends on the building or home design, the rate of air exchange, and the distance of the building or home from the landfill. Chapter Three provides more information about how people are exposed to gases once the gases have entered buildings or homes.

What types of landfills might be found in communities?

Your community may have different types of landfills within it or nearby:

- ***Municipal solid waste (MSW) landfills*** are used to dispose of household wastes and nonhazardous commercial and industrial wastes. More than 6,000 MSW landfills exist across the United States, although fewer than 3,000 of these are currently active and accepting waste. Landfills constructed after 1979 are required, under Subtitle D of the Resource Conservation and Recovery Act (RCRA), to be designed and operated to prevent contaminant migration to the environment. This design may include liners or collection systems. Landfills constructed before 1979 may not have such environmental safeguards.
- ***Open dumps*** are waste disposal areas that were used before 1979 and constructed without any engineering design and siting criteria, and few, if any, regulatory controls. Open dumps do not meet the RCRA Subtitle D regulations. Open dumps may have accepted household wastes, similar to MSW landfills, as well as commercial and industrial wastes. These dumps did not have liners and rarely used daily cover for sanitary wastes. No precautions were taken to prevent contaminant migration to the environment. Most open dumps were discontinued and covered in the 1960s. Unfortunately, the locations of many of these old dumps are not marked on local planning maps. Some of the current operating MSW landfills began in the 1960s as open dumps or are located adjacent to closed dumps.

- ***Construction and demolition (C&D) waste landfills*** are used for the disposal of construction and demolition waste such as wood, sheet rock, gypsum board, concrete, bricks, and paving materials. As with MSW landfills, C& D waste landfills containing nonhazardous materials are regulated under Subtitle D of RCRA.
- ***Hazardous waste landfills*** are used to dispose of wastes characterized under RCRA as "hazardous." These wastes include solvents, industrial wastes, and construction wastes such as asbestos. Operating or recently closed landfills containing hazardous materials are regulated under Subtitle C of RCRA.
- ***Vegetation waste disposal areas,*** also known as "yard waste and stump fill areas," are used to dispose of vegetation wastes. In many states, these disposal areas were unregulated prior to the 1980s. In areas where burning was prohibited, these areas were used by land developers to bury trees and brush cleared from land used for subdivisions and commercial developments.
- ***Animal waste landfills*** are areas where massive amounts of manure and, possibly, animal carcasses are disposed. There are no specific federal regulations for animal waste landfills. State regulations vary among the states that do regulate the animal waste landfills. As a result of the high organic content, methane production can be significant. Decaying manure and carcasses will produce strong odors. Fires have occurred on some animal waste landfills, increasing health and safety concerns of nearby residents.

This publication focuses primarily on MSW landfills. Of all the types of landfills, MSW landfills are the most significant source of landfill gas emissions, because approximately 60% of the waste in a typical MSW landfill is organic. The Web site of EPA's Office of Solid Waste (**http://www.epa.gov/epaoswer/non-hw/muncpl/facts.htm**) is a good source of basic information about MSW landfills. The Solid Waste Association of North America's (SWANA's) Landfill Gas Operation and Maintenance Manual of Practice is another source of general information about landfills; it can be accessed by a search of the U.S. Department of Energy's (DOE) Information Bridge at the Web site **http://www.osti.gov** or by placing an order for a hardcopy from SWANA's Web site at **http://www.swana.org**.

Are landfill gas emissions regulated?

Prior to 1979, landfills were often merely open dumps with few or no controls to prevent contaminant migration to the environment. Open dumps posed significant environmental and public health hazards. They attracted flies and vermin, and fires that could burn for days often broke out. These dumps had no gas collection systems, nor did they have liners to protect groundwater. All types of waste, including hazardous wastes, could be deposited in landfills before 1979. Some of these dumps have been listed as "Superfund" sites and are now being remediated or are on a waiting list to be remediated. No longer legal, open dumps have been closed or converted into MSW landfills. Past dumps with no gas control systems are the landfill sites most likely to have gas emission concerns.

Many state and local governments have regulated landfills since the middle of the twentieth century; however, before 1979, regulation and enforcement varied widely from site to site. In 1979, the federal government began regulating the siting, construction, operation, and closure requirements for landfills under RCRA. Subtitle D of RCRA addresses MSW and nonhazardous landfills and includes requirements for methane monitoring at the landfill perimeter. Subtitle C of

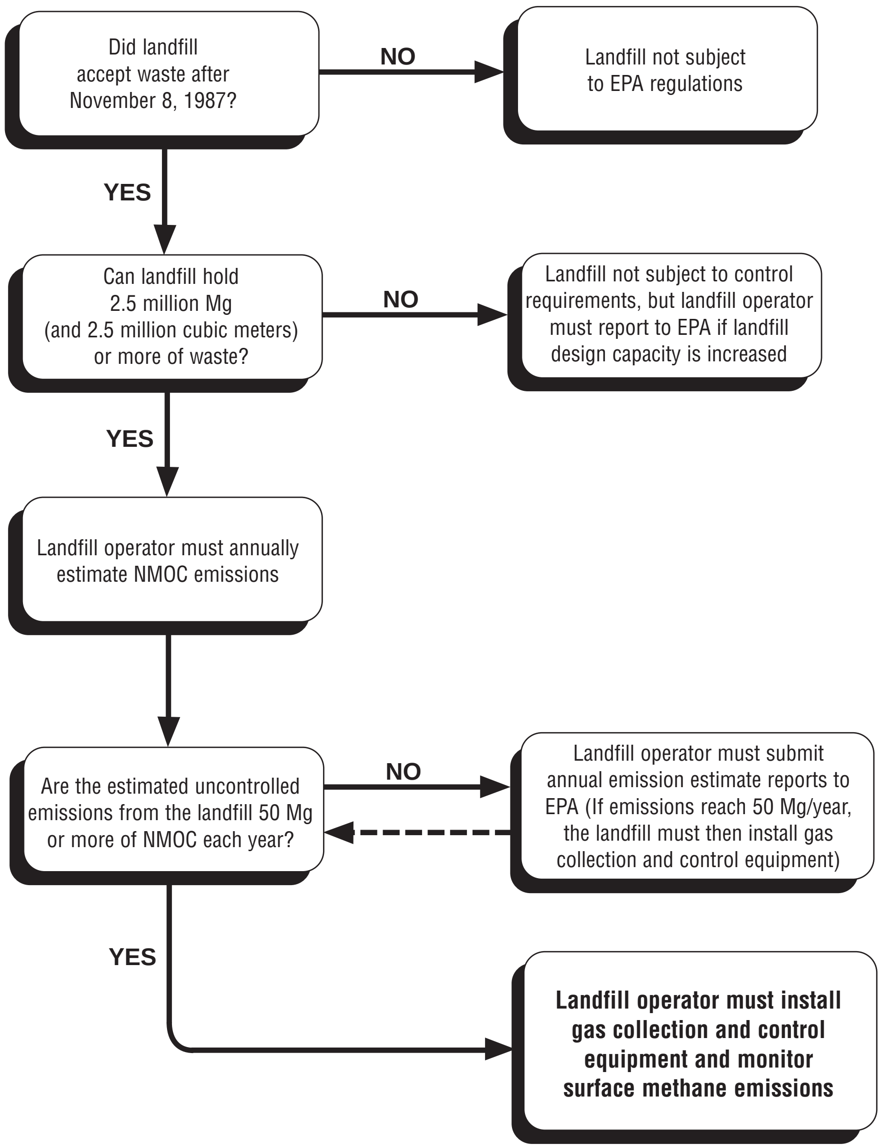
RCRA addresses concerns associated with hazardous waste landfills. In 1996, EPA finalized regulations under the Clean Air Act (CAA)—the New Source Performance Standards and Emissions Guidelines (NSPS/EG)—that address methane and NMOC emissions from MSW landfills. These regulations are described in more detail below, according to the type of waste received by the landfill.

- ***Municipal solid wastes.*** Subtitle D of RCRA regulates the siting, design, construction, operation, monitoring, and closure of MSW landfills. RCRA establishes standards that MSW landfills must meet. These standards are enforced by the state solid waste authority. States may also develop additional standards that are more stringent than RCRA. RCRA requires that owners and operators of MSW landfills ensure that the concentration of methane gas generated by the facility does not exceed 25% of the lower explosive limit (LEL), the lowest percent by volume of an explosive gas in the air that will allow an explosion, for methane in facility structures and that the concentration of methane gas does not exceed the LEL for methane at the facility property boundary. If methane concentrations exceed the LEL at the property boundary, then RCRA requires the landfill owners/operators to notify the proper state authority and develop and implement a plan to correct the problem (see Chapter Three for more information about LELs). The state solid waste authority will determine whether the landfill has properly addressed the problem.

  In 1996, EPA promulgated regulations under the CAA—NSPS/EG—that also address emissions from MSW landfills. These regulations apply to MSW landfills that accepted waste after November 8, 1987. The NSPS/EG require landfills that can hold 2.5 million megagrams (Mg) or more of waste and annually emit 50 Mg or more of NMOCs to install landfill gas collection systems and control landfill gas emissions. The collection systems must meet specific engineering design criteria. Control devices (usually a flare or some other combustion device) must reduce the NMOC emissions from the collected landfill gas by 98% or to a concentration of 20 ppm by volume. Those MSW landfills that are required to install controls based on their NMOC emission rate must also monitor surface methane emissions. If methane emissions are found at concentrations exceeding background levels by more than 500 parts per million (ppm) between 2 and 4 inches from the ground surface, the gas collection system must be adjusted or improved to achieve the 500 ppm level. The NSPS/EG also contain various other testing, monitoring, and reporting requirements that landfills must meet. Figure 2-2 can help determine to what extent, if any, the MSW landfill(s) in the area must comply with the requirements of the NSPS/EG. The NSPS/EG can be found in the Code of Federal Regulations (CFR), at 40 CFR Part 60, Subparts Cc and WWW. Additional information can be found at **http://www.epa.gov/ttn/uatw/landfill/landflpg.html**.

- ***Construction and demolition wastes.*** Most C&D waste is classified as nonhazardous and can be disposed of in an MSW landfill or in a C&D landfill (a landfill that accepts only C&D waste). The siting, design, construction, operation, monitoring, and closure of landfills containing nonhazardous C&D wastes are regulated under Subtitle D of RCRA. Air emissions from C&D landfills are not regulated and are not generally a concern, because C&D wastes do not contain much organic matter (which is necessary to produce landfill gas). However, if gypsum wallboard is present in C&D waste, hydrogen sulfide may be produced, particularly if moisture is introduced into the waste. Because of

Figure 2-2: How to Determine if a Landfill Must Comply with NSPS/EG[a]



[a] The New Source Performance Standards (NSPS) is a federal rule that applies to landfills that started construction or increased their total design capacity after May 30, 1991. The Emission Guidelines (EG) apply to older landfills and are implemented and enforced through state plans (or a federal plan in cases where states have not developed plans). The landfill gas control requirements are the same.

hydrogen sulfide's objectionable rotten-egg odor, C&D landfills that emit hydrogen sulfide often find themselves facing numerous complaints from the surrounding communities. Operators of these landfills often find that they must install gas control systems to reduce odors caused by the hydrogen sulfide gas.

Some C&D wastes may be classified as hazardous wastes because they contain hazardous materials, such as asbestos. Hazardous C&D waste must be disposed of in a hazardous waste landfill, as described below.

- ***Hazardous wastes.*** The siting, design, construction, operation, monitoring, and closure of landfills containing hazardous wastes are regulated under Subtitle C of RCRA. Hazardous waste landfills are strictly regulated because they handle wastes that pose a greater risk to the public than nonhazardous household waste. Air emissions from hazardous waste landfills are not specifically regulated under RCRA Subtitle C. However, Subtitle C does address air emissions from the generation, storage, treatment, and transport of hazardous wastes.

For more information about how U.S. landfills are regulated, visit the Web site of EPA's Office of Solid Waste at **http://www.epa.gov/epaoswer/osw/index.htm**.

Additional Resources

CMHC. 1993. Canada Mortgage and Housing Corporation. Soil gases and housing: a guide for municipalities.

EPA. 1992. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Seminar Publication. Organic air emissions from waste management facilities. EPA/625/R-92/003.

O'Leary P, Walsh P. 1995. C240-A180 Solid waste landfills correspondence course. Lesson 3: Landfill gas movement, control, and uses. Madison, WI: University of Wisconsin, Solid and Hazardous Waste Education Center (originally printed in Waste Age Magazine January 1991–March 1992). January 1995. **http://wissago.uwex.edu/uwex/course/landfill/1.html**.

SWANA. 1997. Solid Waste Association of North America. Landfill Gas Operation and Maintenance Manual of Operation. SR-430-23070. Available at the Department of Energy Information Bridge at the Web site **http://www.osti.gov/bridge/product.biblio.jsp?osti_id=314156**.

References

ATSDR. 1998. Agency for Toxic Substances Disease Registry. U.S. Department of Health and Human Services. Investigation of cancer incidences and residence near 38 landfills with soil gas migration conditions. New York State, 1980-1989. Prepared by the New York State Department of Health, Division of Occupational Health and Environmental Epidemiology, Bureau of Environmental and Occupational Epidemiology. PB98-142144. June 1998.

Crawford JF and Smith PG. 1985. Landfill technology. London: Butterworths.

DOE. 1995. U.S. Department of Energy. Greenhouse gases 1987-1994. **http://www.eia.doe.gov/oiaf/1605/95 report/chap3.html**.

EPA. 1993. U.S. Environmental Protection Agency. Solid waste disposal facility criteria–technical manual. EPA 530-R-93-017. November 1993.

EPA. 1995. U.S. Environmental Protection Agency. Compilation of Air Pollutant Emissions Factors, AP-42, Fifth Addition, Volume 1: Stationary Point and Area Sources. January 1995. **http://www.epa.gov/ttn/chief/ap42/ch02/** Section 2.4—Municipal Solid Waste Landfills.

Tchobanoglous G, Theisen H, and Vigil S. 1993. Integrated Solid Waste Management, Engineering Principles and Management Issues. New York: McGraw-Hill, Inc. pp. 381-417.