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METHODS FOR ESTIMATING GREENHOUSE GAS EMISSIONS FROM MUNICIPAL SOLID WASTE

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INTRODUCTION

The EIIP guidelines are designed to describe emission estimation techniques for greenhouse gas sources in a clear and unambiguous manner and to facilitate preparation of inventories at the state level. This chapter presents the methodology for estimating greenhouse gas emissions from municipal solid waste management. The methodology presented in this chapter has been revised to reflect new activity data, emission factors, and methods pertaining to this source category. Where possible, the methodology has been updated to be consistent with the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*.

Section 2 of this chapter contains a general description of this source category. Section 3 provides a listing of the steps involved in estimating greenhouse gas emissions from municipal solid waste management. Section 4 presents the preferred estimation method. Section 5 provides information on an alternative estimation technique for this source category. A summary of uncertainty for this source category is provided in Section 6. References used in developing this chapter are identified in Section 7.

In addition to these guidelines, there are a series of user friendly spreadsheet tools available to assist in the development of emission inventories at the state level. Please consult the Municipal Solid Waste Module of the State Inventory Tool[1] to calculate emissions from this source category using the preferred emission estimation method.

[1] Note: The spreadsheet tool may have a different order of calculations, and may not show all calculations to the user.

2

SOURCE CATEGORY DESCRIPTION

2.1 EMISSION SOURCES

This chapter includes emission estimation methodologies for landfilling and waste combustion.

In landfills, methane (CH_4) and carbon dioxide (CO_2) are produced from anaerobic decomposition of organic matter by methanogenic bacteria. Organic waste first decomposes aerobically (in the presence of oxygen) and is then decomposed by anaerobic non-methanogenic bacteria, which convert organic material to simpler forms like cellulose, amino acids, sugars, and fats. These simple substances are further broken down to gases and short-chain organic compounds (H_2, CO_2, CH_3COOH, HCOOH, and CH_3OH), which support the growth of methanogenic bacteria. The bacteria further metabolize these fermentation products into stabilized organic materials and "biogas," which consists of approximately 50 percent CO_2 and 50 percent CH_4 by volume. Additionally, some landfills flare recovered landfill gas, which converts the CH_4 portion of the gas to CO_2.

Neither the CO_2 emitted directly as biogas nor the CO_2 emitted from combusting CH_4 at flares is counted as an anthropogenic greenhouse gas emission. The source of the CO_2 is primarily the decomposition of organic materials derived from biomass sources (e.g., crops, forests), and in the United States these sources are grown and harvested on a sustainable basis.[2] Sustainable harvesting implies that photosynthesis (which removes CO_2 from the atmosphere) is equal to decomposition (which adds CO_2 to the atmosphere).

Much of the carbon in landfills that is not converted to CO_2 or CH_4 is stored indefinitely and removed from the pool of carbon available to cycle to the atmosphere, i.e., it is sequestered. In accordance with the Intergovernmental panel on Climate Change (IPCC) guidelines on greenhouse gas accounting (IPCC/UNEP/OECD/IEA 1997), only biogenic carbon (i.e., carbon from plant or animal matter) is counted as sequestered. Plastics that are landfilled represent a transfer of carbon from one long-term carbon pool (oil or natural gas reserves) to another (landfills), and thus are not counted as incremental carbon sequestered.

Waste combustion emits both CO_2 and nitrous oxide (N_2O). CO_2 is produced from oxidation of organic materials in waste, such as paper, food scraps, yard trimmings, and plastic. As with CO_2 from biogas and oxidation of CH_4, CO_2 emissions from biogenic sources (e.g., paper and food

[2] The Intergovernmental Panel on Climate Change's greenhouse gas accounting guidelines (IPCC/UNEP/OECD/IEA 1997) call for counting emissions from biogenic sources when they are harvested on a non-sustainable basis. In the United States, paper, wood, and food are the primary biogenic sources of waste-related CO_2 emissions; these sources are all harvested on a sustainable basis.

scraps) are not counted as a greenhouse gas because they simply return CO_2 that plants previously absorbed through photosynthesis to the atmosphere. However, some CO_2 is from nonbiogenic sources (e.g., plastic and rubber made from petroleum), and is thus counted as a greenhouse gas. Nitrous oxide is produced at the high temperature found in waste combustors by the combination of nitrogen (both nitrogen contained in the waste and nitrogen gas in the air) and oxygen gas in the air.

2.2 FACTORS INFLUENCING LANDFILL METHANE EMISSIONS

CH_4 emissions from landfills are a function of several factors, including:

(1) The total amount of MSW in landfills. While the duration that landfilled waste generates CH_4 varies by landfill, it is generally accepted that this period is approximately 30 years. In other words, waste that was deposited up to 30 years ago is assumed to still generate CH_4 today.[3]

(2) The composition of the waste entering landfills. Municipal solid waste supplies the necessary starting material for CH_4 generation in landfills by providing degradable organic carbon (DOC), which is metabolized by methanogenic bacteria to produce landfill gas. Food waste has a high DOC content, as do some grades of paper (e.g., office paper). Wastes such as metal and glass have no DOC.

(3) The characteristics of landfills receiving waste. In particular, a landfill's size, moisture content, pH level, and temperature can all influence the amount of CH_4 that is generated.

(4) The amount of CH_4 that is recovered and either flared or used for energy. Due to a 1996 U.S. EPA rule that requires gas recovery at large municipal solid waste landfills, the number of landfill gas recovery systems is increasing and the CH_4 generated from landfills is being captured and flared or used as an energy source.[4]

(5) The amount of CH_4 oxidized instead of being released into the atmosphere. While the extent to which CH_4 is oxidized at the landfill surface varies by landfill, an assumption of 10 percent oxidation is currently being used for the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (Liptay et al. 1998).

[3] This assumption is used in developing estimates of landfill CH_4 emissions for the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*.

[4] The rule requires a well-designed and well-operated landfill gas collection system at landfills that (1) have a design capacity of at least 2.5 million metric tons and 2.5 million cubic meters, and (2) emit more than 50 metric tons of nonmethane organic compounds per year (Federal Register 1996).

2.3 FACTORS INFLUENCING WASTE COMBUSTION GREENHOUSE GAS EMISSIONS

The amount of nonbiogenic CO_2 emitted when waste is combusted depends on the amount of nonbiogenic (i.e., derived from "fossil" sources such as petroleum or gas) carbon in the waste, and the percentage of nonbiogenic carbon that is oxidized. Sources of fossil-derived carbon include plastics, textiles, and synthetic rubber. The amount of N_2O emitted when waste is combusted depends on the temperature of the combustion chamber and the amount of nitrogen in the waste.

3

OVERVIEW OF AVAILABLE METHODS

This section presents methods for estimating emissions from municipal solid waste management. Landfilling and combustion are subsets of integrated municipal waste management. Integrated waste management covers a broad spectrum of activities that are generally categorized as source reduction, recycling (including composting), combustion, and landfilling. Source reduction, which reduces the quantity of materials produced and subsequently disposed, results in no waste-related greenhouse gas emissions. Greenhouse gas emissions from recycling and composting are confined to emissions resulting from facility operations and transportation. This chapter discusses emissions from waste disposal through combustion and landfilling, the only two waste-related sources of emissions addressed in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997).[5]

3.1 OVERVIEW OF PREFERRED METHOD FOR ESTIMATING METHANE EMISSIONS FROM LANDFILLS

Because it is impractical to measure methane (CH_4) emissions from each of the nation's numerous landfills, efforts to estimate emissions from landfills rely on a predictive approach. The key factor is the generation of CH_4 within the waste mass (although other factors, such as the rate of oxidation as CH_4 passes through overlying soil, and the presence and efficiency of landfill gas collection systems are also important). There are two basic options for estimating CH_4 generation:

- Determine the emission "potential" of a representative quantity of refuse through theoretical considerations (e.g., carbon content) or laboratory simulation. Scale this value to the state level by estimating the quantity of refuse in landfills statewide.

- Use available data to determine the actual generation rates of CH_4 per unit of refuse and multiply this value by the estimated quantity of refuse disposed, over time, in landfills statewide.

The first approach relies on kinetic models of landfill gas formation or on simulations conducted in laboratories. This method assumes conditions that occur in kinetic models or under laboratory conditions closely simulate actual field conditions. This assumption limits the accuracy of the method because it is difficult to determine whether theoretical or laboratory conditions actually

[5] For a more holistic approach to estimating greenhouse gas emissions from municipal waste management, please refer to the U.S. EPA report entitled *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks* (U.S. EPA 2002b). This report can be found on the Internet at http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm.

simulate field conditions. The second approach relies on actual data instead of theoretical results. When proper data is available, this approach is more accurate and is therefore the preferred method for estimating greenhouse gas emissions from municipal solid waste facilities.

The preferred approach relies on field data rather than theoretical results. Specifically, the approach described below is based on an emissions model developed for the report *Anthropogenic Methane Emissions in the United States: Report to Congress* (U.S. EPA 1993). This method, which is used by EPA in preparing the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002* (U.S. EPA 2004), uses a statistical model in which the CH_4 emission rate is a function of the quantity of waste deposited in landfills (in tons). This rate is expressed in terms of tonnage-based emission factors, which differ for large and small landfills, and for arid and non-arid climates. Emission estimates may be calculated by collecting various state-level data and applying this information to the method. The method presented consists of the following twelve steps:

Step 1: Obtain required data;

Step 2: Estimate waste in place at municipal solid waste (MSW) landfills;

Step 3: Estimate fraction of waste in large versus small MSW landfills;

Step 4: Classify state as arid or non-arid;

Step 5: Estimate CH_4 generated from waste in place at small MSW landfills;

Step 6: Estimate CH_4 generated from waste in place at large MSW landfills;

Step 7: Estimate total CH_4 generated from MSW landfills;

Step 8: Adjust MSW CH_4 generation for flaring and recovery;

Step 9: Adjust MSW CH_4 generation for oxidation;

Step 10: Estimate CH_4 generated from industrial landfills;

Step 11: Sum MSW and industrial CH_4 generation; and

Step 12: Convert to metric tons of carbon equivalent.

The emissions model on which this method is based was developed by examining and confirming data from 85 landfills that recover CH_4 gas to produce energy.[6] The data analyzed identifies the relationships between CH_4 recovery and (1) refuse quantity, (2) refuse characteristics (e.g., moisture content, temperature, and pH), and (3) landfill characteristics (such as age,[7] depth, volume, and surface area).[8] The analysis showed that a simple model using the

[6] It should be noted that if the landfills used in this analysis are not representative of landfills as a whole, then the models used in this analysis may not accurately represent state landfill CH_4 generation.

[7] The analysis assumes that landfilled wastes produce CH_4 over a thirty year period. If the actual period is significantly longer, the emissions may be understated. Conversely, if the period is shorter, the emissions may be overstated.

[8] It should be noted that the analysis used to create the model is based on data describing the CH_4 *recovered* from landfills, with landfill gas collection efficiency used to calculate total CH_4 generation

total amount of waste in place and the landfill's location in an arid or non-arid climate was adequate for estimating CH_4 production. Because this method is based on the total waste in place at a landfill, and not on annual waste generation and disposal rates, it accounts for timed releases of CH_4 instead of assuming that all of the CH_4 generated is released during the year the waste is deposited.

The analysis also indicated that the amount of CH_4 gas generated per unit of waste is higher in landfills with over 1.1 million tons of waste in place than landfills with less than 1.1 million tons of waste in place.[9] In summary, the emissions depend on three key factors: (1) total waste in place; (2) landfill size; and (3) location in an arid or non-arid climate.

The model only determines the amount of gas generated so the results must be adjusted to account for oxidation and CH_4 flared or recovered and used. As previously described, some of the CH_4 produced by landfills is recovered to produce energy or flared to meet environmental and safety requirements.

In sum, CH_4 emissions to the atmosphere may be estimated based on CH_4 production from municipal landfills, CH_4 produced by industrial landfills, CH_4 flared or recovered, and CH_4 oxidized in landfills before being released to the atmosphere. These adjustments can be described as:

Net CH_4 Emissions = Municipal Landfill CH_4 Generation – Municipal Landfill CH_4 Flaring or Recovery - CH_4 Oxidation by Soil at MSW Landfills + Industrial Landfill CH_4 Generation - CH_4 Oxidation by Soil at Industrial Landfills.

MSW landfills are estimated to account for approximately 93 percent of all CH_4 emissions from landfills in the United States (EPA 2002c). Industrial landfills account for the remainder of landfill CH_4 emissions.

3.2 OVERVIEW OF PREFERRED METHOD FOR ESTIMATING WASTE COMBUSTION GREENHOUSE GAS EMISSIONS

The preferred method for estimating waste combustion greenhouse gas emissions involves determining the amount of waste combusted in the state during the inventory year, and multiplying that amount by (1) a carbon dioxide (CO_2) emission factor and (2) a nitrous oxide (N_2O) emission factor. The method uses easily obtained data. Both of these emissions are currently included in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (U.S. EPA 2004). The preferred method for estimating greenhouse gas emissions from waste combustion

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(landfill-specific collection efficiency was available for approximately half of the 85 landfills surveyed, with the remainder using an assumption of 75 percent efficiency). However, the CH_4 recovery information is an imperfect surrogate for actual data on CH_4 generation.

[9] The original data set only included landfills with greater than 1.1 million tons of waste in place. Equations for small landfills were extrapolated from this data set. The equations for large versus small landfills are not congruent at their boundary conditions (1.1 million tons of waste in place).

consists of the following five steps: (1) obtain required data; (2) estimate the quantity of municipal waste combusted; (3) estimate CO_2 emissions from combustion of municipal waste in metric tons of carbon equivalent; (4) estimate N_2O emissions from municipal waste combustion; and (5) convert N_2O emissions from municipal waste combustion to metric tons of carbon equivalent.

3.3 OVERVIEW OF ALTERNATIVE METHODS FOR ESTIMATING LANDFILL METHANE EMISSIONS

Two alternative methods for estimating landfill CH_4 emissions are presented in Section 5. The first method, described in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997), is relatively simple to use; it employs a simple equation and data for which data sources are readily available. The second method is more complex; it involves estimating CH_4 generation over time, based on theoretical first-order kinetic models. Two models are available to conduct this analysis – the Landfill Air Emissions Estimation Model and the LandGEM model. U.S. EPA is currently comparing the CH_4 emission estimates from these models with those generated by other estimation methods.

4

PREFERRED METHODS FOR ESTIMATING EMISSIONS

This section presents the preferred methodologies for estimating methane (CH_4) emissions from landfills, and for estimating carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions from waste combustion.

4.1 METHANE EMISSIONS FROM LANDFILLS

This section provides the preferred methodology for estimating state landfill CH_4 emissions. Readers are encouraged to utilize the Municipal Solid Waste Module of the State Inventory Tool (hereafter referred to as the State Inventory Tool), which provides a user-friendly, step-by-step module for calculating emissions using the methodology described below.

The new methodology for estimating CH_4 emissions from landfills consists of twelve steps:

- Obtain required data;
- Estimate waste in place at Municipal Solid Waste (MSW) landfills;
- Estimate fraction of waste in place in large versus small landfills;
- Classify state as non-arid or arid;
- Estimate CH_4 generated from waste in place at small MSW landfills;
- Estimate CH_4 generated from waste in place at large MSW landfills;
- Estimate total CH_4 generation from MSW landfills;
- Adjust MSW CH_4 generation for flaring and recovery;
- Adjust MSW CH_4 generation for oxidation;
- Estimate CH_4 generated from industrial landfills;
- Sum MSW and industrial CH_4 generation; and
- Convert units to metric tons of carbon equivalent (MTCE).

Step (1): Obtain Required Data

- *Required Data*. The following information is needed to estimate CH_4 emissions from landfills.

  (1) **Waste in place in the state**. For the purposes of this estimation methodology, waste in place is defined as the total quantity of waste that has been landfilled over the previous 30 years (in tons). If waste in place information is unavailable, population data will be required to estimate waste in place.

  (2) **Fraction of waste in place in large versus small MSW landfills**. Large landfills are defined here as those that have a total of more than 1.1 million tons of waste in place.

  (3) **The state's average annual rainfall**.

  (4) **Quantity of landfill CH_4 that is recovered or flared (tons CH_4/year)**.

- *Data Sources.* The following data sources may be used.

  (1) **Waste in place in the state.** State solid waste offices or other state agencies may track the amount of waste in place in the state's landfills. If a state does not have estimates of waste in place, but does have estimates of waste disposal over 30 years, waste in place may be calculated using waste disposal for each 30-year period. If a state has data on waste disposal for recent years, but not for earlier years, waste disposal may be estimated using historical population data and national per capita landfilling rates. If a state has neither waste in place nor disposal data, waste in place may be calculated using the state's historical population data, and national per capita landfilling rates. For waste in place at industrial landfills, formulas shown in Step 10 may be used if state information is not available.

  The U.S. EPA is another possible source of waste in place data for landfills. U.S. EPA has published working drafts of 31 state landfill profiles entitled *Landfill Gas-to-Energy Opportunities: Landfill Profiles for the State of [State]* (U.S. EPA 1999).[10] Landfill profiles may be accessed from the following website: http://www.epa.gov/lmop/proj/profiles.htm. State profiles include only data for large landfills in each state.

  (2) **Fraction of waste in place in large versus small MSW landfills.** The fraction of total waste placed in large and small landfills over the past 30 years may be available from the state solid waste office; if not, it may be estimated using default values shown in Step 3.

[10] Since these profiles are not published annually, users would need to update data sets using more recent data.

(3) **The state's average annual rainfall.** A state is considered arid if average rainfall is less than 25 inches per year. A table provided later in this section lists those states that receive, on average, less than 25 inches of rainfall per year (the arid states). All other states are considered to be non-arid.

(4) **Quantity of landfill CH_4 that is recovered or flared.** Information on landfill CH_4 flaring and recovery may be available from state solid waste offices. Otherwise, these data may be obtained from the State Inventory Tool.[11]

Step (2): Estimate Waste in Place at Municipal Solid Waste Landfills

- If reliable estimates of 30-year waste in place are available, these estimates should be used.

- If 30-year waste in place information is not available, but state data are available on the quantity of waste that has been landfilled over the previous 30 years, waste in place can be calculated using the following equation:

$$WIP_{30} = [\text{waste landfilled (tons)}_{t}] + \ldots + [\text{waste landfilled (tons)}_{t-29}]$$

t = present year

In cases where a state imports or exports waste, the state should use *net* landfilled waste in the above equation.

***Example*:**	A state does not have an estimate of waste in place in 2000, but does know that total waste disposal in the state's landfills was 5,000,000 tons per year from 1971-1980; 6,000,000 tons per year from 1981-1990, and 7,000,000 tons per year from 1991-2000. Total 30-year waste in place in 2000 would then be calculated as follows: Waste in place $(\text{tons})_{2000} = (5{,}000{,}000 \times 10)_{1971\text{-}1980} + (6{,}000{,}000 \times 10)_{1981\text{-}1990} + (7{,}000{,}000 \times 10)_{1991\text{-}2000}$ **= 180,000,000 tons**

- If state data are not available on the total quantity of waste landfilled over the previous 30 years, but *are* available on waste landfilled from 1990-present, waste landfilled may be backcasted using population and per capita landfilling rates, as shown in the following equation:

$$WIP_{30} = WIP_{Known} + WIP_{Backcasted}$$

$$WIP_{Known} = [\text{waste landfilled (tons)}_{t}] + \ldots + [\text{waste landfilled (tons)}_{tk}]$$

t = present year, tk = oldest known year

[11] U.S. EPA develops annual state-specific estimates of CH_4 recovered for landfill gas-to-energy projects or flaring when it develops the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. These data are updated annually in the State Inventory Tool.

$WIP_{Backcasted} = [population \times PCTL^*_{tk-1}] + \ldots + [population \times PCTL^*_{t-29}]$

PCTL (Per Capita Tons Landfilled)

** This is estimated by taking the oldest known PCTL and factoring in the U.S. growth rates to backcast the PCTL for each successive year. (See Table 13.4-1 for growth rates)*

$PCTL_{tk} = waste\ landfilled\ (tons) / population_{tk}$

$PCTL_{tk-1} = PCTL_{tk} \times (1 - U.S.\ growth\ rate)$

Table 13.4-1: U.S. Per Capita Tons Landfilled (PCTL) Growth Rate by Decade

-0.02 if 1990 ≤ t > 2000
0.003 if 1980 ≤ t > 1990
0.020 if 1970 ≤ t > 1980
0.030 if 1960 ≤ t > 1970

- If data are not available on either waste in place or waste landfilled, waste in place can be calculated using state population and national average per capita disposal rates, as shown in the following equation:

$WIP_{30} = [population \times U.S.\ PCTL_{t}] + \ldots + [population \times U.S.\ PCTL_{t-29}]$

t = present year (See Table 13.4-2 for U.S. PCTL data)

Table 13.4-2: United States Per Capita Municipal Solid Waste Landfilling Rate (tons/capita)

1960-1969		1970-1979		1980-1989		1990-1999		2000-2009	
1960	0.31	1970	0.43	1980	0.54	1990	0.56	2000	0.46
1961	0.32	1971	0.44	1981	0.55	1991	0.55	2001	0.45
1962	0.33	1972	0.45	1982	0.55	1992	0.53	2002	NA
1963	0.34	1973	0.47	1983	0.55	1993	0.52	2003	NA
1964	0.36	1974	0.48	1984	0.55	1994	0.50	2004	NA
1965	0.37	1975	0.49	1985	0.55	1995	0.47	2005	NA
1966	0.38	1976	0.50	1986	0.56	1996	0.46	2006	NA
1967	0.39	1977	0.51	1987	0.56	1997	0.47	2007	NA
1968	0.41	1978	0.52	1988	0.56	1998	0.47	2008	NA
1969	0.42	1979	0.53	1989	0.56	1999	0.48	2009	NA

Source: U.S. EPA 2002a, 2003. These values are derived from U.S. population and waste landfilled data.

NA = data not yet available

* The decrease in per capita waste disposal from 1990-2000 was largely due to increases in the United States' recycling rate over this period.

***Example*:** Suppose a state does not have an estimate of waste in place in 2000, but does know that waste disposal in 2000 was 5,000,000 tons. For purposes of this example, assume that total state population was 10,000,000 in 2000 and 9,000,000 in 1999. Total 30-year waste in place in 2000 would then be calculated as follows:

Step 1: Estimate per capita waste landfilled in 2000.

5,000,000 tons/10,000,000 persons = 0.5 tons/capita

Step 2: Estimate per capita waste landfilled in 1999.

0.5 tons/capita x [1-(-0.02)] = 0.51 tons/capita

Step 3: Estimate waste landfilled in 1999.

0.51 tons/capita x 9,000,000 persons = 4,590,000 tons

Step 4: Estimate waste landfilled for previous years.

Repeat steps 2 and 3 above to estimate waste landfilled for all years, 1971-1998.

Step 5: Estimate waste in place.

Sum the individual estimates of waste landfilled from 1971 to 2000 to obtain waste in place in 2000.

***Example*:** A state has neither an estimate of waste in place or waste disposal in 2000. For the purposes of this example, assume that total state population was 10,000,000 in 2000 and had grown by 100,000 every year since 1971. Total 30-year waste in place in 2000 would then be calculated as follows:

$\text{Waste in place (tons)}_{2000}$ = (10,000,000 persons x 0.46 tons/person) + (9,900,000 persons x 0.48 tons/person) +…+ (7,100,000 persons x 0.44 tons/person) = **131,534,219 tons**

Step (3): Estimate Fraction of Waste in Place in Large vs. Small Municipal Solid Waste Landfills

Once the total quantity of waste in place has been estimated, the next step is to estimate the fraction of total waste in place in large versus small landfills. For this estimation methodology, a large landfill is defined as having more than 1.1 million tons of waste in place.

- Some states may have information on the fraction of waste disposed in large landfills. If this information is not available, then the fraction may be estimated using default values shown in Table 13.4-3.

Table 13.4-3: Default Values for the Fraction of Waste in Large Versus Small Landfills

Region	States Located in Region	Fraction of Waste Landfilled at Large Landfills
Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont	89%
Southeast	Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Virginia, West Virginia	73%
Midwest	Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, Oklahoma, North Dakota, South Dakota, Texas, Wisconsin	81%
West	Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, Wyoming	86%

Source: Derived from U.S. EPA 1988.

***Example*:** Assume that total landfilled waste for a state is 90 million tons, of which 20 percent is in small landfills and 80 percent is in large landfills. Therefore, the amount of waste in place in small and large landfills is the following:

Waste in place at small landfills: 20% x (90 million tons) = **18 million tons**

Waste in place at large landfills: 80% x (90 million tons) = **72 million tons**

Step (4): Classify State as Non-arid or Arid

Moisture is an important factor in the production of CH_4 in landfills. Landfills in non-arid climates produce more CH_4 per unit of waste in place than do landfills in arid climates.

- Different CH_4 emission estimates have been developed for non-arid states and for arid states. Table 13.4-4 lists those states that are classified as arid states, i.e., states that have an average rainfall of less than 25 inches per year. All other states are considered to be non-arid states.

- If a state has distinct arid and non-arid areas—particularly in areas where landfills are located—then the additional steps described at the end of Steps 5 and 6 should be taken.

Table 13.4-4: Arid States (States with average annual rainfall less than 25 inches)

Arizona	Montana	North Dakota
California	Nebraska	South Dakota
Colorado	Nevada	Utah
Idaho	New Mexico	Wyoming

Source: Department of Commerce 2002.

Step (5): Estimate Methane Generated from Waste in Place at Small Municipal Solid Waste Landfills

- Based upon the emissions model, the following equations are used to estimate the range of CH_4 generated from small landfills based on the quantity of waste in place (WIP). The equations below should be used for non-arid and arid states, respectively.

Non-arid: CH_4 *(tons/year) = 0.002695 tons* CH_4*/yr/ton WIP x WIP (tons)*

Arid: CH_4 *(tons/year) = 0.002079 tons* CH_4*/yr/ton WIP x WIP (tons)*

Example	CH_4 generated at small landfills for a *non-arid* state with 18 million tons of waste in place at small landfills would be estimated as follows: 0.002695 (tons CH_4/yr/ton waste in place) x 18 million tons = **48,510 tons CH_4/yr**

- If a state is partially arid, then a weighted average based on the percentage of waste disposed in arid regions may be used to estimate the CH_4 generated from small landfills. If the amount of waste in small landfills in arid and non-arid regions is known, then both equations above may be used, using the appropriate factor in each equation.

Step (6): Estimate Methane Generated from Waste in Place at Large Municipal Solid Waste Landfills[12]

- The equations below should be used to estimate CH_4 generated from large landfills for non-arid states and arid states, respectively.

Non-arid: CH_4 *(tons) = (N x 3,218 tons* CH_4*) + [0.002002 tons* CH_4*/yr/ton WIP x WIP (tons)]*

Arid: CH_4 *(tons) = (N x 3,218 tons* CH_4*) + [0.001232 tons* CH_4*/yr/ton WIP x WIP (tons)]*

Where:

N = number of large landfills

Example:	CH_4 generated for an *arid* state that has five large landfills and waste in place at large landfills of 72 million tons would be estimated as follows: CH_4 (tons) = (5 x 3,218 tons CH_4) + (0.001232 tons CH_4/yr/ton x 72 million tons) = **104,794 tons CH_4**

- If a state is partially arid, then a weighted average based on the percentage of waste disposed in arid regions may be used to estimate the CH_4 generated from large landfills. If the amount of landfilled waste in arid and non-arid regions is known, then both of the above equations may be used, using the appropriate factor in each equation.

[12] In the State Inventory Tool, default values for the number of large landfills are based on data on total number of landfills by state, as reported in the *BioCycle* journal.

Step (7): Estimate Total Methane Generated from Municipal Solid Waste Landfills

- Total CH_4 generated from MSW landfills is the sum of CH_4 generated at small landfills (Step 5) and CH_4 generated at large landfills (Step 6).

Step (8): Adjust Municipal Solid Waste Methane Generation for Flaring and Recovery

- Some states have landfills that either flare some of the CH_4 that is produced or recover the CH_4 and use it as an energy source. As mentioned in Step 1, U.S. EPA develops annual state-specific estimates of CH_4 recovered for landfill gas-to-energy projects or flaring, which are included in the State Inventory Tool. Once CH_4 flaring and/or recovery is estimated, a preliminary estimate of CH_4 emissions can be calculated as follows:

Preliminary Net CH_4 Emissions = Total CH_4 Generated – CH_4 Flared or Recovered for Energy

***Example*:**	For a state that has a total landfill CH_4 generation of 168,000 tons per year and recovers or flares 10,000 tons of landfill CH_4 per year, the net CH_4 emitted would be calculated as follows: 168,000 tons CH_4 generated - 10,000 tons CH_4 recovered or flared = **158,000 tons CH_4**

Step (9): Adjust Municipal Solid Waste Methane Generation for Oxidation

CH_4 may be oxidized in the top layer of soil over the landfill. Regardless of whether a landfill gas recovery system is in place, uncollected CH_4 will pass upward through the landfill cover or surrounding soils, where it may be oxidized (Whalen, Reeburgh and Sandbeck 1990). The amount of oxidation that occurs is uncertain and depends on latitude (affecting surface soil temperature), soil characteristics, and other factors. Currently, there is limited research available to assist in quantifying the amount of CH_4 that is oxidized during this process. Four papers published in 1997 address this question (Kjeldsen, Dalager and Broholm 1997, Bogner, Spokas and Burton 1997, Liptay, et al. 1998, and Bogner, Meadows and Czepiel 1997). U.S. EPA assumes that 10 percent of the CH_4 generated that is not flared or recovered is oxidized in the soil. Accordingly, CH_4 generated (minus the amount flared or recovered) should be multiplied by 90 percent to account for oxidation.[13]

- Once the adjustment for oxidation has been made, the result is total CH_4 emissions from MSW landfills, as shown below:

Total CH_4 Emissions from MSW = Preliminary Net CH_4 Emissions x 0.90

Step (10): Estimate Methane Generated from Industrial Landfills

CH_4 is also generated from waste deposited in non-hazardous industrial landfills. Although CH_4 generation from non-hazardous industrial landfills is believed to be small relative to that from MSW landfills, industrial landfill CH_4 generation is still a significant source of CH_4 emissions.

[13] Where state-specific oxidation rates are available, use 1 minus the oxidation rate in place of the 90 percent default value presented here.

CH_4 generation from industrial landfills does not include CH_4 generation from industrial waste disposed of into MSW landfills. This CH_4 generation is already accounted for under MSW landfills.

- The quantity of waste in industrial landfills and its CH_4 generation rate must be estimated, because data are generally not available. Based on estimates of the quantity of waste in place at industrial landfills and on the estimated organic content of industrial landfills compared to MSW landfills, U.S. EPA (1993) estimated that CH_4 generation from industrial landfills in the United States is approximately 7 percent of CH_4 generation from MSW landfills in the United States, prior to adjusting for flaring and recovery or oxidation. This 7 percent value may be used to estimate state CH_4 generation from industrial landfills, as shown in the following equation:

Preliminary CH_4 Emissions from Industrial Landfills = Preliminary Net CH_4 Emissions from MSW Landfills x 0.07

- Since industrial waste is also assumed to oxidize at the landfill surface, the preliminary estimate of CH_4 emissions from industrial landfills must also be multiplied by 0.90 to adjust for oxidation, as shown in the following equation:

Total CH_4 Emissions from Industrial Landfills = Preliminary Net CH_4 Emissions from Industrial Landfills x 0.90

***Example*:**	For a state that has an estimated 108,000 tons of CH_4 generated from large MSW landfills and 49,000 tons from small MSW landfills, CH_4 emissions from industrial waste landfills would be calculated as follows: (108,000 tons CH_4 + 49,000 tons CH_4) x 0.07 = 10,990 tons CH_4 (pre-oxidation) 10,990 tons CH_4 x 0.90 = **9,891 tons CH_4**

Step (11): Sum Municipal Solid Waste and Industrial Methane Generation

- Total CH_4 emissions equals total MSW CH_4 emissions (Step 9), plus total industrial landfill CH_4 emissions (Step 10), as shown in the following equation:

Total CH_4 Emissions = Total CH_4 Emissions from MSW Landfills + Total CH_4 Emissions from Industrial Landfills

Step (12): Convert Units to Metric Tons of Carbon Equivalent

- Perform the calculation shown below to convert the emissions to MTCE. To do so first multiply by 0.907 to convert from tons to metric tons. Then multiply metric tons of CH_4 by the ratio of the atomic weight of carbon to the molecular weight of carbon dioxide (12/44), and by the Global Warming Potential (GWP) of CH_4 (21), as shown in the following equation:

CH_4 Emissions (MTCE) = CH_4 Emissions (tons) x 0.907 metric tons/ton x 21 x 12 C/44 CO_2

4.2 GREENHOUSE GAS EMISSIONS FROM WASTE COMBUSTION

Combustion of municipal waste results in emissions of CO_2 and N_2O (U.S. EPA 2002b).[14] Organic material is converted into CO_2 and water when it is burned. Only the emissions of CO_2 from fossil sources are counted in greenhouse gas inventories. CO_2 originating from burning of biogenic organic materials (provided that they are harvested on a sustainable basis) is regarded as closing the loop on the natural photosynthesis-respiration process, and thus is not counted as an anthropogenic source of greenhouse gas emissions.

To develop an estimate of CO_2 emissions, combustion of the fossil-derived carbon in MSW is calculated for three waste categories: plastics, textiles, and synthetic rubber (U.S. EPA 2002a).[15] In the national inventory, U.S. EPA uses information on the typical composition of discards in the U.S. solid waste stream to estimate the mass of each of these waste types that is combusted, and then estimates the proportion of each material that comprises fossil carbon. Finally, by assuming that 98 percent of the fossil carbon is converted to CO_2 in the combustion process (with the balance remaining with the ash), U.S. EPA estimates total emissions for each waste and sums them. At the state level, this sequence of calculations differs only in that state-level (rather than national) estimates of waste mass must be developed.

According to the Intergovernmental Panel on Climate Change (IPCC), MSW combustion results in measurable emissions of N_2O (IPCC/UNEP/OECD/IEA 1997). The IPCC (2000) compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. U.S. EPA estimated the average emissions from waste combustion by averaging the midpoints of the ranges for the combustion technology used in the United States (U.S. EPA 2004).[16]

The methodology for estimating state-specific CO_2 and N_2O emissions from waste combustion consists of five steps: (1) obtain required data; (2) estimate the quantity of municipal waste combusted; (3) estimate the CO_2 emissions from combustion of municipal waste; (4) estimate

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[14] For comparison to U.S. waste combustion methodology and estimates, refer to the Energy chapter of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002* (U.S. EPA 2004) and the Waste chapter for all editions prior to *1990-2000*.

[15] In the national greenhouse gas inventory, U.S. EPA also includes combustion of synthetic rubber in tires and carbon black in tires. Because it is difficult to characterize combustion of tires at the state level, and it is a very minor source, we have omitted it from this guidance.

[16] In addition, many waste combustors in the United States produce electricity, thus displacing electricity generated from fossil fuels and reducing electric utility greenhouse gas emissions. For the purposes of conducting a greenhouse gas inventory, however, these utility greenhouse gas reductions are already reflected in the inventory of fossil fuel greenhouse gas emissions. Similarly, many U.S. waste combustors recover scrap steel from the combustor ash; when this steel is recycled there are energy savings (and greenhouse gas reductions) compared to manufacturing the same amount of steel from virgin inputs. Again, for greenhouse gas inventory purposes, these greenhouse gas impacts need not be counted in the waste combustion analysis because they are already reflected in the inventory of fossil fuel and industrial sector greenhouse gas emissions.

N_2O emissions from municipal waste; and (5) convert units to MTCE. This methodology is also included in the State Inventory Tool.

Step (1): Obtain Required Data

- *Required Data*. The information needed to estimate emissions of fossil-derived CO_2 and N_2O from combusted MSW includes the total amount of MSW combusted annually in the state, in tons. Additionally, for estimating CO_2 emissions from combustion for each of the waste categories, obtain information on the proportion of plastics, synthetic rubber, and synthetic fiber contained in the waste discarded each year.

- *Data Sources*. If in-state data sources provide the information needed, those sources should be used. If not, the quantity of MSW combusted in the state may be calculated using an annual survey of municipal waste management practices published every other year by *BioCycle* magazine entitled *State of Garbage in America* (published by the JG Press in Emmaus, Pennsylvania, typically in the December issue). Although the *BioCycle* survey presents figures for waste management practices by state, these figures include industrial and construction and demolition (C&D) waste disposed at MSW facilities. Another key source of information is the annual U.S. EPA report entitled *Municipal Solid Waste in the United States: [Year] Facts and Figures* (formerly entitled *Characterization of Municipal Solid Waste in the United States*) (U.S. EPA 2003). This reference provides information on the composition of waste discards and is the source of information on plastics, textiles, and rubber at the national level. It is anticipated that few states will have information on the composition of waste delivered to combustors in the state, so it will generally be necessary to assume that national composition represents state composition.

Step (2): Estimate the Quantity of Municipal Waste Combusted

- In order to estimate MSW combusted in the state, use the *BioCycle* estimate of waste disposal amounts and the correlating fraction combusted[17] to estimate the amount combusted by that state.

Example:	According to *BioCycle*'s 2001 Survey, the amount of waste disposed of in Michigan in 2000 was 18,717,000 tons, with 9 percent combusted. (18,717,000 tons MSW disposed x 9% combusted) = **1,684,530 tons MSW combusted** in Michigan

Step (3): Estimate Carbon Dioxide Emissions from Combustion of Municipal Waste

The steps below explain the methodology for estimating CO_2 emissions from the combustion of plastics, synthetic rubber in MSW (excluding rubber in tires), and synthetic fibers. Note that the approach described in sub-steps (a) and (b) can be expedited by multiplying the waste combusted in the state (from Step 2) by the emission factor provided in Column 5 of Table 13.4-5 (this is also provided in the State Inventory Tool for the full time series from 1990 through 2002).

[17] *BioCycle* generally refers to waste incineration rather than waste combustion.

(a) Calculate Amount of Fossil-Derived Materials Combusted

- If state specific data are not available, these amounts will have to be derived using national data. To estimate the quantities of plastic, synthetic rubber, and synthetic fiber waste combusted in the state, first estimate the proportion of discards for each material by dividing the quantity of each material discarded nationally by the total MSW discarded nationally. These discarded values, obtained from the U.S. EPA's *Municipal Solid Waste Report* and calculated into proportions, are presented in Table 13.4-5 for 2000 and in the State Inventory Tool for 1990 through 2000. The proportions of discards from individual plastic resins and synthetic rubber product categories are also provided for those states wishing to evaluate emissions for these more specific materials.

- Multiply each of these estimated proportions of discarded plastics, synthetic rubber, and synthetic fibers by the quantity of waste combusted in the state for each year (calculated in Step 2).

Example According to U.S. EPA's *Municipal Solid Waste in the United States: 2000 Facts and Figures*, 23,370,000 tons of plastics, 3,380,000 tons of synthetic rubber (excluding rubber in tires), 8,110,000 tons of synthetic fibers, and a total of 164,280,000 tons of MSW were discarded in the United States in 2000 (U.S. EPA 2002a; U.S. EPA 2003). Using the waste combusted quantity for Michigan (calculated in Step 2), the quantities of each material combusted in Michigan in 2000 can be calculated as follows:

Plastics

23,370,000 tons plastics discarded in United States ÷ 164,280,000 tons MSW discarded in United States = 14.23% plastics discarded

14.23% x 1,684,530 tons MSW combusted in Michigan = **239,709 tons plastics combusted** in Michigan

Synthetic Rubber in MSW

3,380,000 tons synthetic rubber discarded in United States ÷ 164,280,000 tons MSW discarded in United States. = 2.06% synthetic rubber discarded

2.06% x 1,684,530 tons MSW combusted in Michigan = **34,701 tons synthetic rubber combusted** in Michigan

Synthetic Fibers

8,110,000 short synthetic fibers discarded in United States ÷ 164,280,000 tons MSW discarded in United States = 4.94% synthetic fibers discarded

4.94% x 1,684,530 MSW combusted in Michigan = **83,216 tons synthetic fibers combusted** in Michigan

(b) Multiply by Carbon Content and Fraction Oxidized

- Multiply the scaled quantity of plastics (or resin quantities), synthetic rubber (or product sub-categories), and synthetic fibers combusted for the state by the corresponding carbon contents and the assumed fraction oxidized of 98 percent. Carbon contents for each of the materials are provided in Table 13.4-5.

Example Using the 2000 waste combusted quantities for plastics, synthetic rubber in MSW, and synthetic fibers for Michigan (calculated in Step 3a), carbon emissions in tons are estimated as follows:

Plastics

239,709 tons plastics combusted x 0.78 carbon content x 0.98 = **183,234 tons C**

Synthetic Rubber

34,701 tons synthetic rubber combusted x 0.85 carbon content x 0.98 = **28,906 tons C**

Synthetic Fibers

83,216 tons synthetic fibers combusted x 0.70 carbon content x 0.98 = **57,086 tons C**

(c) Convert Carbon Emissions to Metric Tons of Carbon Equivalent

- Multiply carbon emissions for each type of material by 0.9072 metric tons per ton to calculate carbon emissions in units of MTCE.

(d) Calculate Total Carbon Dioxide Emissions for Plastics, Synthetic Rubber, and Synthetic Fibers in Units of Carbon

- To estimate the total carbon emissions from waste combustion in the state, sum the total emissions from combustion of plastics, synthetic rubber in MSW, and synthetic fibers in MTCE.

***Example*:** To convert 2000 emissions from tons of carbon to MTCE, perform the following calculations for each material:

Plastics

183,234 tons C x 0.9072 metric tons/ton = **166,230 MTCE**

Synthetic Rubber

28,906 tons C x 0.9072 metric tons/ton = **26,224 MTCE**

Synthetic Fibers

57,086 tons C x 0.9072 metric tons/ton = **51,788 MTCE**

Total Emissions

(166,230 + 26,224 + 51,788) = **244,242 MTCE**

Table 13.4-5: 2000 Proportion of Discards, Carbon Content, Fraction Oxidized, and Emission Factor by Material

Material	Proportion of Discards	Carbon Content	Fraction Oxidized	Emission Factor [a]
Plastics[18]	**14.23%**	**78%**[b]	**98%**	**0.1104**
PET	1.25%	63%	98%	0.0078
HDPE	2.68%	86%	98%	0.0229
PVC	0.85%	38%	98%	0.0032
LDPE/LLDPE	3.40%	86%	98%	0.0290
PP	2.03%	86%	98%	0.0173
PS	1.39%	92%	98%	0.0127
Other	2.62%	66%[c]	98%	0.0171
Synthetic Rubber in MSW	**2.06%**	**85%**	**98%**	**0.0174**
Durables	1.55%	85%	98%	0.0131
Non-Durables	0.49%	85%	98%	0.0042
Clothing and Footwear	0.33%	85%	98%	0.0028
Other Non-Durables	0.16%	85%	98%	0.0014
Containers and Packaging	0.02%	85%	98%	0.0002
Synthetic Fibers	**4.94%**	**70%**[d]	**98%**	**0.0343**

[a] The emission factor is multiplied by tons of waste combusted, and yields tons carbon. The values in this column are the product of the values in the preceding three columns.

[b] Weighted average of plastic resin carbon contents.

[c] Weighted average of other plastics produced.

[d] Weighted average of carbon contents of the major fiber types produced.

Source: Proportion of discards were calculated using U.S. EPA 2003. Carbon contents were calculated using U.S. EPA 2002a. Assumed fraction oxidized taken from U.S. EPA 2004.

Step (4): Estimate Nitrous Oxide Emissions from Municipal Waste

- Multiply the state tonnage of MSW combusted (from Step 2) by the emission factor of 0.000044 tons of N_2O emitted per ton of MSW combusted.

Example:	Total N_2O emissions from combustion of waste in Michigan in 2000 can be calculated as follows: 1,684,530 tons x (0.000044 tons of N_2O/ ton MSW combusted) = **74 tons N_2O**

[18] Resin abbreviation translations: PET (polyethylene terephthalate), HDPE (high density polyethylene), PVC (polyvinyl chloride), LDPE/LLDPE (linear low density polyethylene), PP (polypropylene), and PS (polystyrene).

Step (5): Convert Units to Metric Tons of Carbon Equivalent

- Convert the emissions in tons to metric tons by multiplying by 0.9072 metric tons per ton.
- Convert the emissions to MTCE by first multiplying by the global warming potential GWP of N_2O and then multiplying by the ratio of the atomic weight of carbon to the molecular weight of CO_2. The GWP of N_2O is 310 and the mass ratio is 12 C/44 CO_2.

N_2O (MTCE) = N_2O (tons) x 0.9072 metric tons/ton x 310 x 12 C/44 CO_2

Example:	Emissions of N_2O from combustion are converted to MTCE as follows:
	74 tons N_2O x 0.9072 metric tons/ ton = 67 metric tons N_2O
	67 metric tons N_2O x 310 x (12 C/44 CO_2) = **5,665 MTCE**

5

ALTERNATIVE METHODS FOR ESTIMATING EMISSIONS

This section presents two alternative methods for estimating methane (CH_4) emissions from landfills if states are not able to obtain the data required to use the recommended method.

5.1 ESTIMATING LANDFILL METHANE EMISSIONS ASSUMING INSTANTANEOUS EMISSIONS

The simplest methodology for estimating CH_4 emissions from landfills is based on a mass balance approach, where an instantaneous release of CH_4 is assumed to enter the atmosphere during the same year that refuse is placed in the landfill (Bingemer and Crutzen 1987). This approach is used in the *Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC/UNEP/OECD/IEA 1997) as the default methodology for estimating CH_4 emissions from solid waste disposal sites. Bingemer and Crutzen divide the world into four economic regions: United States/Canada/Australia, Other OECD, USSR/Eastern Europe, and Developing Countries. Then they determine how much municipal solid waste (MSW) is produced for each region and how much of that MSW is degradable organic carbon. To calculate the annual emissions from MSW, Bingemer and Crutzen used the following equation:

CH_4 Emissions = Total MSW Generated (lbs/yr) x MSW Landfilled (%) x DOC in MSW (%) x Fraction Dissimilated DOC (%) x 0.5 lbs CH_4/lb Biogas x Conversion Factor (16 lbs CH_4/12 lb C) – Recovered CH_4 (lbs/yr)

Note that the first two factors in the equation above may be obtained from individual state U.S. EPA Solid Waste Divisions. The following default values for North America may be used for the third and fourth factors in the equation above:

- Degradable Organic Carbon (DOC) in MSW = 18-21 percent (IPCC 1996)
- Fraction Dissimilated = 77 percent (IPCC/UNEP/OECD/IEA 1997, Bingemer and Crutzen 1987)

The revised IPCC guidelines add a factor to Bingemer and Crutzen's equation to adjust for oxidation of landfill CH_4. However, the default value for the oxidation factor is currently set at zero, pending the availability of further data (IPCC/UNEP/OECD/IEA 1997). In the United States, it would be acceptable to complete the equation above and follow the methodology presented in Section 4.1 Step 9.

5.2 ESTIMATING LANDFILL METHANE EMISSIONS BASED ON A FIRST-ORDER KINETIC MODEL

A more complex method for estimating CH_4 emissions from landfills is based on a first-order kinetic model of CH_4 production, which considers timed releases of CH_4 to the atmosphere (U.S. EPA 1998). U.S. EPA's Landfill Air Emissions Estimation Model (LAEEM), a modified version of the Scholl Canyon model, is described in detail in *1998 Compilation of Air Pollutant Emission Factors, AP-42* (U.S. EPA 1998). LAEEM is also available through the Office of Air Quality Planning and Standards, Technology Transfer Network Website (OAQPS TTN Web) in the Clearinghouse for Inventories and Emission Factors (CHIEF) technical area (Internet address: http://www.epa.gov/ttn/chief).

LAEEM is most effective when applied to individual landfills, but it may also be applied at the state level. Estimates have also been made for the United States using this model or its precursors (e.g., Colt et al. 1990). The model assumes that gas production will be highest upon initial placement of waste in the landfill (after a certain negligible lag period during which anaerobic conditions are formed). The rate then decreases exponentially (i.e., undergoes first-order decay) as the availability of DOC decreases (U.S. EPA 1990). The model equation and variables are described briefly below:

$$Q_{CH4} = L_O \times R \times (e^{-kc} - e^{-kt})$$

where,

- Q_{CH4} = *CH_4 generation rate at year t (ft^3/yr)*
- L_0 = *CH_4 generation potential (ft^3/ton of refuse)*
- R = *average annual refuse acceptance rate during active life (tons/yr)*
- k = *CH_4 generation rate constant (yr^{-1})*
- c = *time since closure (c = 0 for active landfills) (yr)*
- t = *time since initial refuse placement (yr)*

Default values for some of these variables are given in Table 13.5-1. Site-specific landfill information must be supplied for variables R, c, and t. In cases where refuse acceptance rates are unknown, R can be estimated by dividing waste in place by the years the landfill was actively accepting waste. If it is necessary to calculate R, note that the waste deposited in landfill cells that exclusively accept nondegradable refuse (e.g., concrete, brick, stone, glass, plaster, wallboard, piping, plastics, and metal objects) need not be included in the estimate of waste in place.

At specific landfills, the CH_4 generation potential, L_0, varies as a function of the moisture and organic content of the refuse. The CH_4 generation constant, k, is a function of several factors, including moisture, pH, temperature, and other factors (U.S. EPA 1998). This constant determines how quickly the CH_4 generation rate decreases. The default values shown below represent the best fit for 21 landfills. Note, however, that predicted CH_4 emissions ranged from 38 to 492 percent of actual emissions, so there is considerable variability among landfills, and considerable uncertainty in this (and the other) estimation methods.

Table 13.5-1: Data Elements and Corresponding Sources

Data Element Needed	Default Values	Source of Data
L_0	3,530 ft^3/ton	U.S. EPA 1998a
R	–	Landfill owner
K	0.04/yr if ≥ 25 inches of rain 0.02/yr if < 25 inches of rain	U.S. EPA 1998a
T	–	Landfill owner
C	–	Landfill owner

6

UNCERTAINTY SUMMARY

This chapter presents methodology for estimating methane (CH_4) emissions from landfills and for estimating carbon dioxide (CO_2) and nitrous oxide (N_2O) from waste combustion. Uncertainty surrounds key elements of these calculations, including the activity data and factors.

6.1 UNCERTAINTY OF ESTIMATION METHANE EMISSIONS FROM MUNICIPAL LANDFILLS

There are several sources of uncertainty associated with the recommended method for estimating CH_4 emissions from landfills. The actual number and size of landfills and other waste management facilities are not known with certainty. Many small and unregulated facilities may exist that are not included in these estimates, resulting in underestimation of emissions. CH_4 production is also impacted by temperature, rainfall, and landfill design, characteristics that vary by each landfill and cannot be accounted for individually. Additionally, the time period over which landfilled waste produces CH_4 also is not certain. At present, the assumed time period is thirty years; this could be an overestimate or underestimate. This methodology is based on information from CH_4 recovered from various landfills, which may not be representative of landfills as a whole. Little information is available on the amount of CH_4 oxidized during diffusion through the soil cover over landfills. The assumed ten percent is based on limited measurements.

The method of estimating CH_4 emissions from small landfills is less accurate than the one for large landfills. This difference is due to the fact that more CH_4 measurements were taken from large landfills than small ones. In addition, the methodology presented here assumed the waste composition of all landfills is the same; in reality, waste in different landfills likely varies in composition. The presence of landfill gas recovery systems may affect activity in the anaerobic zones of landfills, since active pumping may draw more air into the fill, thus inhibiting methanogenesis.

6.2 UNCERTAINTY OF ESTIMATING GREENHOUSE GAS EMISSIONS FROM MUNICIPAL SOLID WASTE COMBUSTION

There are several sources of uncertainty surrounding the estimates of CO_2 and N_2O from waste combustion, including combustion and oxidation rates, average carbon contents, and biogenic content. Due to variation in the quantity and composition of waste, the combustion rate is not exact. Similarly, the oxidation rate is uncertain because the efficiency of individual combustors varies depending on type of waste combusted, moisture content, and other factors. Average carbon contents are used for "other" plastics, synthetic rubber, and synthetic fibers. However, the actual carbon content of these materials may vary depending on the specific composition of each material. Nonbiogenic CO_2 emissions from waste combustion depend on the amount of

nonbiogenic carbon in the waste, and the percentage of nonbiogenic carbon that is oxidized. EPA used simplifying assumptions that (1) all carbon in textiles is non-biomass carbon, i.e., petrochemical-based plastic fibers such as polyester, and (2) the category of rubber and leather is composed almost entirely of rubber. The resulting estimate of CO_2 emissions from waste combustion slightly overstates the emissions.

7

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