DRAFT RULE LANGUAGE
For Advisory Committee Review

Chapter 173-441 WAC
Reporting Emissions of Greenhouse Gases

Appendix B:

FUGITIVE METHANE EMISSIONS FROM LANDFILLS

TCR Local Government Operations Protocol, Chapter 9 Solid Waste Facilities

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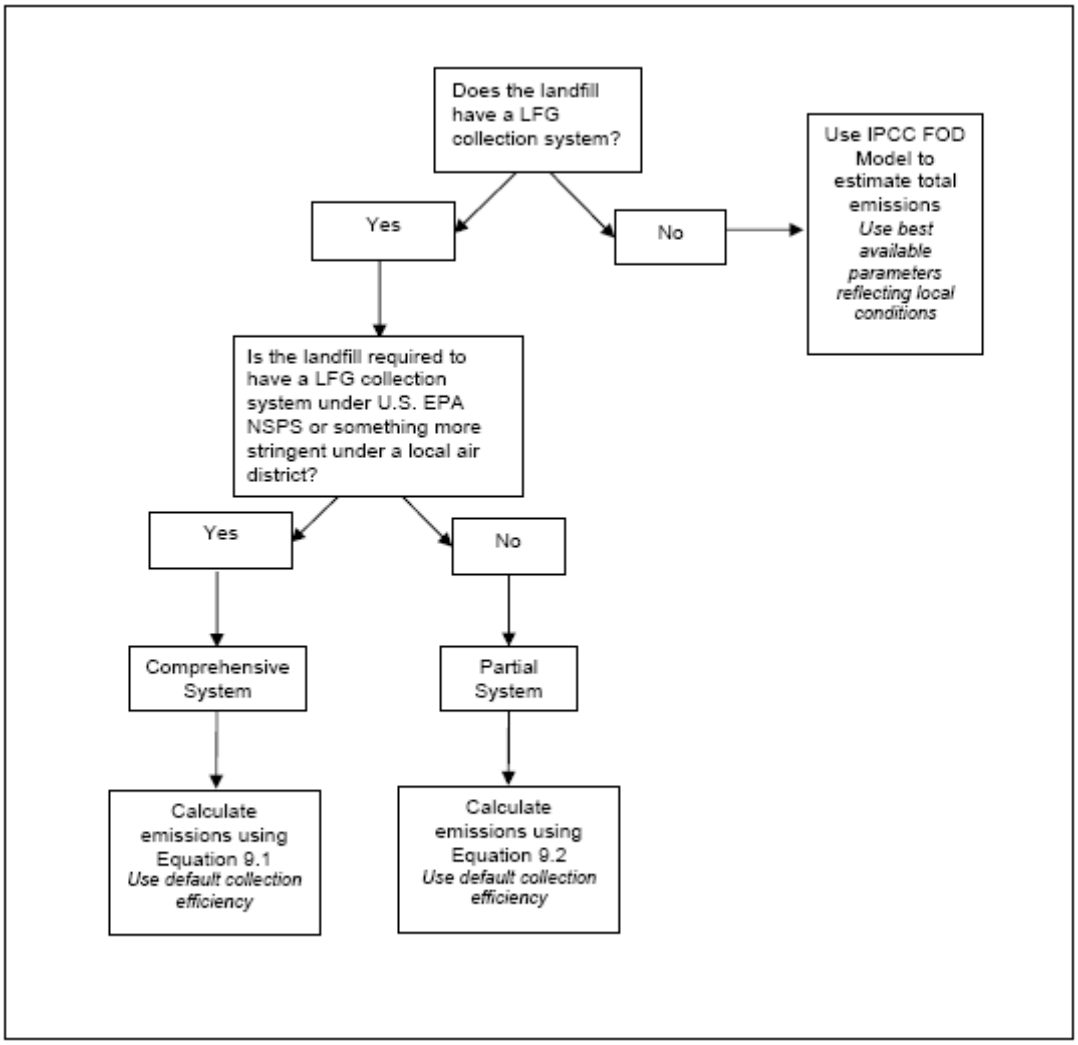

9.3.1 Landfills with No LFG Collection System

If your landfill does not have a LFG collection system in place, the fugitive CH4 emissions can be
estimated using a first order kinetics model based on the amount of waste disposed annually, its
composition, and the climate and operational conditions of the landfill. The IPCC has developed a First Order Decay (FOD) model for national governments to quantify waste emissions as part of its 2006 guidelines. This model is based on the assumption that the amount of carbon that will decay is directly proportional to the current amount of material available in the landfill to
undergo decay. The excel-based tool provided with this Protocol is based on the IPCC FOD model. The California Air Resources Board developed this tool for local governments that facilitates entry for waste characterization numbers and local parameters from US EPA, state or local environmental agencies. You can download the excel-based FOD model from www.arb.ca.gov/cc/protocols/localgov/localgov.htm

For those local governments that do not have facility-specific data to use in the model, default values are provided below for many variables. These default values are also available in the tool itself.

To estimate the fugitive CH4 emissions from your landfill, follow the steps below:
1. Determine the annual waste deposited in the landfill historically;
2. Input data into the excel-based FOD model; and
3. Calculate fugitive emissions in metric tons CH4 and CO2e.

Step 1: Determine the annual waste in place deposited in the landfill historically.
This should include all waste deposited for all years from the opening year of the landfill up to the year you wish to estimate emissions for. If the opening year is not known, then assume the opening year was 60 years prior to the calendar year for which the estimate is desired.
If you do not have all the years of waste deposition data, use the guidance in Box 9.1 to estimate data for the missing years. Also, your state waste board may have records of the waste deposited in individual landfills going back in time.

Box 9.1 How to Estimate Annual Waste in Place (WIP)

1. Obtain population estimates from the U.S. Census Bureau for the jurisdiction(s) depositing waste in your landfill for all years for which you have missing waste data.

2. Use the known waste deposition data for the year closest to the missing year and multiply this by the ratio of population for the year you want to estimate divided by the population for the known waste deposition year. Repeat this to estimate annual WIP for all of the missing years.

Step 2: Input data into the excel-based FOD model.
Use the excel-based FOD model provided with the Protocol to generate estimates of the amount of CH4 generated for the year in question, in units of metric tons of CH4 generated per year.
Below are the facility-specific data that you need to provide about your landfill in order to run the FOD model:

- Annual waste in place from Step 1 above (tons)
- Annual greenwaste, compost and biosolids used for daily cover, if applicable (tons)
- Waste characterization (percentage per waste type, default values available in Table 9.3 and Table 9.4)
- Landfill's open year
- Landfill's close year (if applicable)
- Fraction of CH4 in LFG from source testing (default value available)
- Average annual rainfall at landfill (inches/year) to determine appropriate methane generation rate constant (k) value (See Table 9.5)

The FOD model uses a series of equations to calculate the amount of CH4 generation based on the above inputs. The summary of primary IPCC FOD equations as applied by the ARB excel tool is presented in Table 9.2.

Table 9.2 Primary Equations from FOD Model

ANDOC (metric tons) = WIPyear (short tons) x 0.9072 (metric tons/short ton) x TDOC x DANF
CH_4 generation (metric tons) = $\{ANDOC_{year-start} \times [1 - \exp^{-[k]}] - ANDOC_{deposited-last\ year} \times [1/k \times (\exp^{-[k \times (1-M/12)]} - \exp^{-[k]}) - (M/12) \times \exp^{-[k]}] + ANDOC_{deposited-same\ year} \times [1 - ((1/k) \times (1 - \exp^{-[k \times (1-M/12)]}) + (M/12))]\} \times F_{CH4}$
CH_4 emitted (metric tons) = [CH_4 Generation (metric tons CH_4)] x (1 –OX)
CH_4 emitted (metric tons CO_2e) = CH_4 emitted (metric tons CH_4) x GWP

Where

Term		Value	Value
WIP	=	Waste-in-Place (wet weight, short tons)	User Input
TDOC	=	Total Degradable Organic Carbon fraction of the total WIP (metric tons of TDOC/metric tons of Total WIP)	Defaults provided Table 9.6
DANF	=	Decomposable Anaerobic Fraction of the TDOC capable of decomposition in anaerobic conditions (metric tons of ANDOC/metric tons of TDOC)	Defaults provided Table 9.7
ANDOC	=	Anaerobically Degradable Organic Carbon (metric tons of carbon)	Calculated
$ANDOC_{year-start}$	=	ANDOC in place at the beginning of the inventory year in question	Calculated
$ANDOC_{deposited-last\ year}$	=	ANDOC deposited during the previous inventory year	Calculated
$ANDOC_{deposited-same\ year}$	=	ANDOC deposited during the inventory year in question	Calculated
exp	=	Exponential Function exp [x]	
k	=	Methane Generation Rate Constant	Defaults provided Table 9.5
M		Assumed delay before newly deposited waste begins to undergo substantial anaerobic decomposition (Months)	6[1]
F_{CH4}	=	Fraction of decomposing carbon converted into CH_4	0.5[1]
OX	=	Oxidation Factor	.10[1]
GWP	=	Global Warming Potential to convert metric tons of methane into metric tons of CO_2 equivalents (CO_2e).	21

[1] Source: IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 3, 3.15, 3.19 (2006).

Table 9.3 Default US Waste Characterization (1960-present)

Waste Type	Waste Type (%) by Year								
	1960	1970	1980	1990	1995	2000	2001	2002	2003-present
Newspaper	6.4%	6.4%	5.9%	4.8%	3.9%	3.7%	2.1%	1.9%	1.4%
Office Paper	10.7%	11.3%	12.0%	13.1%	15.0%	14.8%	14.5%	14.7%	14.1%
Corrugated Boxes	10.8%	13.5%	11.5%	10.5%	10.3%	10.3%	9.8%	9.8%	9.3%
Coated Paper	2.2%	2.0%	2.4%	2.1%	1.8%	1.5%	1.3%	1.2%	1.4%
Food	14.8%	11.3%	9.5%	12.1%	13.4%	15.6%	16.2%	16.1%	16.4%
Grass	12.1%	10.3%	10.1%	9.0%	6.6%	3.6%	3.8%	3.8%	3.8%
Leaves	6.1%	5.1%	5.0%	4.5%	3.3%	1.8%	1.9%	1.9%	1.9%
Branches	6.1%	5.1%	5.0%	4.5%	3.3%	1.8%	1.9%	1.9%	1.9%
Lumber	3.7%	3.3%	5.1%	7.0%	7.3%	7.1%	7.4%	7.4%	7.5%
Textiles	2.1%	1.8%	1.7%	3.3%	4.5%	5.3%	5.6%	5.7%	6.0%
Diapers	0.1%	0.3%	1.4%	1.6%	1.9%	2.0%	2.1%	2.1%	2.1%
Construction/Demolition	2.6%	2.5%	3.5%	3.9%	4.5%	4.8%	5.0%	5.1%	5.2%
Medical Waste	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Sludge/Manure	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Source: US EPA Municipal Solid Waste publication: http://www.epa.gov/msw/pubs/03data.pdf.
These default waste characterization values are used in the FOD model for all states 1960-1995, and for all states except California 1960-present.

Omitted table 9.4 California Waste Characterization

Table 9.5 Default K Values

Average Rainfall (inches/year)	k
<20	0.020
20 - 40	0.038
>40	0.057

Source: EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006, Annex 3.14 (2008).

Table 9.6 Total Organic Degradable Carbon per Waste Type (TDOC)

Waste Type	TDOC	Source
Newspaper	46.5%	EPA
Office Paper	39.8%	EPA
Corrugated Boxes	40.5%	EPA
Coated Paper	40.5%	EPA
Food	11.7%	EPA
Grass	19.2%	EPA
Leaves	47.8%	EPA
Branches	27.9%	EPA
Lumber	43.0%	IPCC
Textiles	24.0%	IPCC
Diapers	24.0%	IPCC
Construction/Demolition	4.0%	IPCC
Medical Waste	15.0%	IPCC
Sludge/Manure	5.0%	IPCC

Sources:
EPA *Solid Waste Management and Greenhouse Gasses: A Life-Cycle Assessment of Emissions and Sinks*, Exhibits 7-2, 7-3 (May 2002).
IPCC *Guidelines for National Greenhouse Gas Inventories*, Chapter 2, Table 2.4, 2.5 and 2.6 (2006).

Table 9.7 Default Decomposable Anaerobic Fraction (DANF) of the TDOC per waste type

Waste Type	DANF	Source
Newspaper	16.1%	EPA
Office Paper	87.4%	EPA
Corrugated Boxes	38.3%	EPA
Coated Paper	21.0%	EPA
Food	82.8%	EPA
Grass	32.2%	EPA
Leaves	10.0%	EPA
Branches	17.6%	EPA
Lumber	23.3%	CEC
Textiles	50.0%	IPCC
Diapers	50.0%	IPCC
Construction/Demolition	50.0%	IPCC
Medical Waste	50.0%	IPCC
Sludge/Manure	50.0%	IPCC

Sources: EPA *Solid Waste Management and Greenhouse Gasses: A Life-Cycle Assessment of Emissions and Sinks* Exhibits 7-2, 7-3 (May 2002).
CEC *Inventory of California Greenhouse Gas Emissions and Sinks: 1990-2004* (December 2006).
IPCC *Guidelines for National Greenhouse Gas Inventories*, Chapter 3, 3.13 (2006).

Step 3: Calculate fugitive emissions in metric tons CH4 and CO2e.
The FOD model will estimate the annual fugitive CH4 emissions from your landfill in metric tons, and will use a GWP of 21 to convert metric tons of CH4 into metric tons of CO2 equivalent.

9.3.2 Landfills with Comprehensive LFG Collection Systems

Fugitive CH4 emissions from a landfill with an active and comprehensive LFG collection system can be derived using the data on actual LFG collected and applying a standard collection efficiency. For the purposes of this Protocol, the LFG collection system is considered to be comprehensive if the landfill is required to have a LFG collection system under US EPA's New Source Performance Standards (NSPS), or a system more stringent than NSPS as dictated by a local air district.

Below are the facility-specific data that you will use with Equation 9.1 in order to estimate the fugitiveCH4 emitted by your landfill:

- Annual landfill gas collected
- Fraction of CH4 in LFG from source testing (default value available)

Equation 9.1	Landfills with Comprehensive LFG Collection Systems

CH_4 emitted (metric tons CO_2e) =

LFG collected x CH_4% x {(1 - DE) + [((1 – CE) / CE) x (1 – OX)]} x unit conversion x GWP

Where:

Term		Description	Value
LFG collected	=	Annual LFG collected by the collection system (MMSCF)	user input
CH_4%	=	Fraction of CH_4 in LFG	0.5, if no facility-specific value is available
DE	=	CH_4 Destruction Efficiency, based on the type of combustion/flare system.	.99[1]
CE	=	Collection Efficiency	0.75
OX	=	Oxidation Factor	0.10[2]
Unit conversion	=	Applies when converting million standard cubic feet of methane into metric tons of methane (volume units to mass units)	19.125
GWP	=	Global Warming Potential to convert metric tons of methane into metric tons of CO_2 equivalents (CO_2e).	21

Sources:
[1] EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006*, Chapter 8, 8-4 (April 2008).
[2] IPCC *Guidelines for National Greenhouse Gas Inventories*, Chapter 3, 3.15, 3.19 (2006).

Step 1: Determine the annual landfill gas collected for the landfill.
This data should be in units of million standard cubic feet (a standard cubic foot is measured at 60 degrees F and standard atmospheric pressure). This is called LFG (MMSCF) in Equation 9.1.
If this year happens to be the first year of operation of the system, use the estimation methodology in Section 9.3.1.

Step 2: Determine the methane fraction from the annual landfill gas data you collected.
If you perform source testing on the LFG according to the requirements of a local, state or national agency, you can use your site specific data for CH4% in Equation 9.1.
If you do not perform site-specific source testing, use the default methane fraction of 50%.

Step 3: Apply a standard collection efficiency of 75%.
The AP 42 emission factors for waste/landfills in the controlled emissions section states that landfill gas collection systems are not 100% efficient in collecting gas and therefore emissions of methane will still occur. Based on reported collection efficiencies between 60% – 85%, a value of 75% collection efficiency is stated as most commonly used19, and is used in this Protocol as a conservative default collection efficiency.

Step 4: Determine the methane destruction efficiency of the control device.
You have the option to use either the default value of .99, or use site-specific methane destruction efficiencies that has been accepted for reporting purposes by a regulatory agency.

Step 5: Account for cover soil oxidation.
Assume a cover soil oxidation value (OX) of 10%.

Step 6: Convert CH4 to CO2e.

Use a GWP of 21 to convert metric tons of methane into metric tons of CO2 equivalent.

9.3.3 Landfills with Partial LFG Collection Systems

Fugitive CH4 emissions for a landfill with a partial LFG collection system can be derived using the data on actual LFG collected together with a standard collection efficiency and a factor to account for emissions from the uncollected area of the landfill. For the purposes of this Protocol, a LFG collection system is considered to be comprehensive only if the landfill is required to have a LFG collection system under US EPA NSPS, or a system more stringent than NSPS as dictated by a local air district. Thus, if you landfill is not subject to NSPS, your LFG collection system is considered partial.

Below are the facility-specific data that you will use with Equation 9.2 in order to estimate the fugitive CH4 emitted by your landfill:

- Annual landfill gas collected
- Fraction of CH4 in LFG from source testing (default value available)
- Factor to account for emissions from the uncollected surface area of the landfill

Equation 9.2	Landfills with Partial LFG Collection Systems
CH_4 emitted (metric tons CO_2e) =	
LFG Collected x CH_4% x {(1-DE) + [(1/CE) x (1-OX)] x [AF + (1-CE)]} x unit conversion x GWP	

Where:

Term		Description	Value
LFG collected	=	Annual LFG collected by the collection system (MMSCF)	user input
CH_4%	=	Fraction of CH_4 in LFG	0.5, if no source testing data is available
DE	=	CH_4 Destruction Efficiency, based on the type of combustion/flare system.	.99[1]
CE	=	Collection Efficiency (Collected LFG/Total Generation LFG). It is a function of multiple variables, active/passive systems, size of open face, type of cover and liner, etc.	0.75
OX	=	Oxidation Factor	0.10[2]
AF	=	Uncollected Area Factor (Uncollected surface area of the LFG collection system / Collected surface area under the influence of a LFG collection system.	user input
Unit conversion	=	Applies when converting million standard cubic feet of methane into metric tons of methane (volume units to mass units)	19.125
GWP	=	Global Warming Potential to convert metric tons of methane into metric tons of CO2 equivalents (CO_2e).	21

Sources:
[1] US EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006*, Chapter 8, 8-4 (April 2008).
[2] IPCC *Guidelines for National Greenhouse Gas Inventories*, Chapter 3, 3.15, 3.19 (2006).

Step 1: Determine the annual landfill gas collected for the landfill.

This data should be in units of million standard cubic feet (a standard cubic foot is measured at 60 degrees F and standard atmospheric pressure). This is called LFG (MMSCF).

If this year happens to be the first year of operation of the system, use the estimation methodology in Section 9.3.1.

Step 2: Determine the CH4 fraction from the annual landfill gas data you collected.
If you perform source testing on the LFG according to the requirements of a local, state or national agency, you can use your site specific data for CH4% in Equation 9.2.
If you do not perform site-specific source testing, use the default methane fraction of 50%.

Step 3: Determine the uncollected area factor for the landfill.
Uncollected Area Factor = Uncollected surface area of the LFG collection system / Collected surface area under the influence of a LFG collection system. The collected surface area is calculated by determining the sum of each extraction well's design radius of
influence, excluding any overlap. Refer to your LFG system design engineer for information on
determining the well design's radius of influence.

Step 4: Apply a standard collection efficiency of 75%.
The AP 42 emission factors for waste/landfills in the controlled emissions section states that landfill gas collection systems are not 100% efficient in collecting gas and therefore emissions of methane will still occur. Based on reported collection efficiencies between 60% – 85%, a value of 75% collection efficiency is stated as most commonly used,20 and is used in this Protocol as a conservative default collection efficiency.

Step 5: Determine the methane destruction efficiency of the control device.
You have the option to use either the default value of .99, or use site-specific CH4 destruction efficiencies that has been accepted for reporting purposes by a regulatory agency.

Step 6: Account for cover soil oxidation.
Assume a cover soil oxidation value (OX) of 10%.

Step 7: Convert CH4 to CO2e.
Use a GWP of 21 to convert metric tons of CH4 into metric tons of CO2 equivalent.

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