

# Technical Guidance Document on Estimating, Measuring and Monitoring Landfill Methane

December 2025



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December 2025

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- Study to Develop Technical Guidance on Methodologies to Estimate, Measure, and Monitor Methane Emissions from Landfills, Jacobs Engineering Group, 2021
- Review of Landfill Methane First-Order Decay Model Rate Constants (k) and Oxidation Factors, iSWM Consulting Ltd, 2021

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## List of Abbreviations

C&D	Construction and demolition
CFR	Clean Fuel Regulations
CH <sub>4</sub>	Methane
CO <sub>2</sub>	Carbon dioxide
DOC	Degradable organic carbon
DOC <sub>f</sub>	Fraction of DOC that decomposes
ECCC	Environment and Climate Change Canada
FID	Flame ionization detector
FOD	First order decay
GHG	Greenhouse gas
GPS	Global positioning system
GWP	Global warming potential
ICI	Industrial/commercial/institutional
IPCC	Intergovernmental Panel on Climate Change
LDAR	Leak detection and repair
LFG	Landfill gas
MCF	Methane correction factor
MRV	Measurement, reporting and verification
MSW	Municipal solid waste
N <sub>2</sub>	Nitrogen gas
NDIR	Non-dispersive infrared
NIR	National Inventory Report on Greenhouse Gas Sources and Sinks
OTM-51	Other Test Method 51
PLC	Programmable logic controller
SCADA	Supervisory control and data acquisition
SEM	Surface emissions monitoring
TDLAS	Tunable diode laser absorption spectroscopy

# 1. Introduction

This document was developed to provide a Canadian technical reference on estimating, measuring and monitoring landfill methane generation and emissions. In addition to supporting emissions reporting required under various federal, provincial and territorial programs and regulations, quantification of methane at landfills assists in accomplishing the following goals:

- Designing emission mitigation measures
- Assessing the effectiveness of emission reduction approaches
- Identifying areas where additional methane control measures may be needed
- Demonstrating methane reductions

## 1.1 Background

Methane is a powerful greenhouse gas (GHG) responsible for roughly 30% of global warming since pre-industrial times. In 2023, emissions from Canadian landfills accounted for 17% of national methane emissions and 3% of national GHG emissions. The Government of Canada's commitments to acting on climate change include reducing methane emissions. [Faster and Further: Canada's Methane Strategy](#) underscored the commitment to taking comprehensive domestic actions to reduce methane emissions, including reductions in the waste sector.

Environment and Climate Change (ECCC) has undertaken work to support methane emission reductions at landfills receiving municipal solid waste (MSW). The quantification of methane generation, capture and emissions at landfills is a central part of federal policies and activities related to tracking and reducing landfill methane emissions, which include:

- [Greenhouse Gas Reporting Program](#): Facilities that emit GHGs (including methane) in amounts of 10,000 tonnes or more in carbon dioxide equivalent units per year are required to report emissions to ECCC on an annual basis
- Greenhouse Gas Offset Credit System: The federal offset protocol for [Landfill methane recovery and destruction](#) requires the quantification of GHG (methane) emissions under baseline and project scenarios
- [Clean Fuel Regulations](#) (CFR): Landfill methane generation must be estimated to assess the eligibility to claim methane emission reductions from landfill gas management in the CFR's fuel carbon intensity calculations
- Canada's [National Inventory Report: Greenhouse Gas Sources and Sinks in Canada](#): The annual inventory provides an estimate of national emissions of GHGs, including methane
- Federal funding programs: Programs that have provided funding for projects targeting reduction of landfill methane emissions have included requirements to quantify future emission reductions

## 1.2 Federal Landfill Methane Regulations

In 2025, the Government of Canada published the federal *Landfill Methane Regulations*, which aim to reduce methane emissions from landfills receiving MSW. Owners and operators of regulated landfills will be required to calculate methane generation; monitor and comply with methane concentration limits on the landfill surface; limit venting to the atmosphere; recover landfill gas into methane destruction

devices or energy recovery systems; monitor the performance of landfill gas recovery systems; and detect and repair methane leaks. Information on the *Landfill Methane Regulations'* applicability as well as monitoring and reporting requirements can be found at [Landfill Methane Regulations](#).

This technical guidance document provides additional background information on the technologies and approaches that may be used to comply with the Regulations. However, it also includes information that is beyond the scope of the Regulations. **With respect to regulatory obligations, the text of the *Landfill Methane Regulations* takes precedence over this document.**

In applicable sections of this document, a summary of requirements under the *Landfill Methane Regulations* is provided in an outlined box. The relevant paragraph or subparagraph of the Regulations is shown in italics (e.g. *4(1)(b)*).

### 1.3 Objectives

This technical guidance document presents approaches to evaluating methane generation and emissions with the intent to encourage the use of consistent methodologies at landfills across Canada.

This document describes best practices and standardized procedures for estimating methane generation, identifying locations where methane emissions are occurring, and quantifying methane emission rates at landfills. A landfill methane generation modelling tool was also developed in tandem with this technical guidance document. To request a copy of this tool, please contact: [ges-dechets-ghg-waste@ec.gc.ca](mailto:ges-dechets-ghg-waste@ec.gc.ca).

The document includes the following sections:

- Modelling landfill methane generation (Section 2)
- Monitoring methane recovery (Section 3)
- Landfill gas wellfield monitoring (Section 4)
- Equipment leak detection (Section 5)
- Measuring surface methane concentrations (Section 6)
- Quantifying methane emissions (Section 7)

The technologies available to measure methane emissions are evolving rapidly. This guidance document provides specific guidance for those technologies that are currently available for tasks such as identifying methane leaks and measuring surface methane concentrations. It also describes new technologies for which standardized methods are not yet available but that are capable of measuring methane concentrations or quantifying methane emissions. This document will be updated, from time to time, as additional standardized methodologies are developed.

### 1.4 Landfill methane basics

When MSW is deposited in a landfill, it first undergoes aerobic (in the presence of oxygen) decomposition which produces primarily carbon dioxide (CO<sub>2</sub>) and only a small amount of methane (CH<sub>4</sub>). Typically, within the first year following waste deposition, anaerobic (without oxygen) conditions are established and methanogenic (methane-producing) bacteria begin to generate methane. At steady state, landfill gas (LFG) contains between 40 and 60% methane by volume, a similar proportion of carbon dioxide and small amounts of other constituents. Most LFG will be generated within the first 20 years

following waste deposition but generation can continue for several decades following closure of a landfill.

LFG can migrate laterally through the subsurface or upward through the landfill cover. As LFG passes through a cover system that includes soil or other organic materials, a portion of the methane is oxidized by bacteria to produce carbon dioxide. The proportion of methane oxidized in landfill covers depends on the integrity, composition and moisture content of the cover material. Some methane may also be emitted into the atmosphere through the active working face of the landfill and through penetrations and fissures in the cover system. Landfill methane emissions will vary over time as a result of weather conditions (barometric pressure, precipitation, frozen conditions) and landfill operating practices.

The most common approach to controlling methane emissions from MSW landfills is by installing infrastructure to actively recover LFG, which is then either flared or utilized to generate fuel or energy.

The primary approach to quantifying methane emissions from landfills requires an accounting of the fate of all generated methane. The mass balance approach assumes that the quantity of methane generated within the landfill is equal to the quantity of methane recovered, emitted, and oxidized (off-site, subsurface migration is assumed to be zero). The mass balance is shown in Equation 1.

*Equation 1. Landfill methane mass balance*

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$CH_4_{generated} = CH_4_{recovered} + CH_4_{emitted} + CH_4_{oxidized}$		
where		Units
$CH_4_{generated}$	= Total mass of CH <sub>4</sub> generated at the landfill by waste decomposition (described in Section 2)	tonnes CH <sub>4</sub>
$CH_4_{recovered}$	= Total mass of CH <sub>4</sub> recovered by the LFG recovery system (described in Section 3)	tonnes CH <sub>4</sub>
$CH_4_{emitted}$	= Total mass of CH <sub>4</sub> emitted to the atmosphere from the landfill (described in Section 7)	tonnes CH <sub>4</sub>
$CH_4_{oxidized}$	= Total mass of CH <sub>4</sub> oxidized by methanotrophic bacteria in the landfill cover materials (described in Section 7)	tonnes CH <sub>4</sub>

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## 2. Modelling landfill methane generation

The quantity of methane that will be generated within a landfill can be estimated using mathematical models. Modelling methane generation at a landfill may be completed for the following reasons:

- To identify regulatory obligations
- To support LFG recovery system design
- To support calculation of annual methane emissions and collection efficiency

### 2.1 First order decay methane generation models

The industry standard approach for estimating methane generation at landfills uses a First Order Decay (FOD) model. There are a number of FOD models utilized in Canada. In addition to these publicly available models, some engineering consultants have developed their own models and model parameters to support more site-specific estimates of methane generation.

#### Intergovernmental Panel on Climate Change Model

The Intergovernmental Panel on Climate Change (IPCC) [methane generation model](#) was most recently updated in 2019 (IPCC 2019). The updated IPCC model accounts for the variability in degradation of a wide range of waste categories, rather than modelling degradation using bulk waste characteristics. This allows for a more robust model that better represents landfill conditions; therefore, the updated model has the potential to produce more accurate methane generation estimates than other FOD models. The current Canadian *National Inventory Report on Greenhouse Gas Sources and Sinks* (NIR) (ECCC 2025b) uses this model and its default parameters for certain waste categories.

#### LandGEM - Landfill Gas Emissions Model

LandGEM was developed by the U.S. Environmental Protection Agency (US EPA) for regulatory and GHG emissions inventory purposes. Methane generation potential ( $L_0$ )<sup>1</sup> values for bulk waste are provided, as are five options for decay rate constant (k) values, which are reflective of climate and moisture conditions. The default parameters to be selected in LandGEM depend on the intended use of the model: for regulatory or inventory reporting purposes (Krause and Thorneloe 2024).

#### Alberta Model

A methane generation model is provided along with the Government of Alberta's [Technical guidance for quantification of specified gas emissions from landfills](#) (Alberta Environment 2008). This model supports quantification of annual methane generation. The Alberta model can be used for compliance with Alberta's regulations and for calculation of methane reductions under Alberta's carbon offset protocols.

#### British Columbia LFG Generation Estimation Tool

The British Columbia Ministry of the Environment and Climate Change Strategy [model](#) was developed in 2009 to support a BC regulatory requirement for methane generation assessment and reporting (BC

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<sup>1</sup> Methane generation potential ( $L_0$ ) is a parameter calculated as the product of DOC,  $DOC_f$ , MCF, fraction of methane in LFG by volume, and the molecular weight ratio of  $CH_4/C$

MOE 2009). The model provides default  $L_0$  and  $k$  values for three categories of waste – relatively inert, moderately decomposable, and decomposable.

## 2.2 ECCC Landfill Methane Modelling Tool

ECCC developed a Landfill Methane Modelling Tool that can be used to estimate methane generation at Canadian landfills. This model must be used by landfills required to calculate annual methane generation under the *Landfill Methane Regulations*. The Modelling Tool is included as an accompanying Microsoft Excel file to this Technical Guidance Document. To request a copy of this tool, please contact: [ges-dechets-ghg-waste@ec.gc.ca](mailto:ges-dechets-ghg-waste@ec.gc.ca).

The methodology used in the model calculations aligns with the IPCC Waste Model, as described in Volume 5, Chapter 3 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), and the *2019 Refinement to the 2006 IPCC Guidelines* (IPCC 2019).

The ECCC model uses a multi-phase approach, calculating methane generation from different waste materials (as opposed to utilizing parameters representing bulk waste), therefore allowing for site-specific adjustments to the composition of MSW deposited in the landfill in a given year. The Modelling Tool includes the option to use either IPCC (wet/dry) or precipitation-based decay rates which enable the user to account for site-specific climate conditions and management practices. The complete list of parameter values used in the Modelling Tool (including  $DOC$ ,  $DOC_f$  and  $k$ ) is provided in Appendix A.

### Model parameters

The following parameters are used in the model:

- Degradable organic carbon ( $DOC$ ): the portion of the organic carbon in each waste material category that is available for decomposition.  $DOC$  values used in the model are provided in Appendix A1
- Fraction of  $DOC$  that decomposes ( $DOC_f$ ): the fraction of  $DOC$  in each waste material category that will decompose under anaerobic conditions in the landfill to generate methane.  $DOC_f$  values used in the model are provided in Appendix A1
- Methane correction factor ( $MCF$ ): a factor based on the estimated fraction of waste that decays aerobically and does not produce methane. The  $MCF$  considers the decomposition of waste under different solid waste landfill management practices. An  $MCF$  of 1 is used in the Modelling Tool, representing the correction factor for anaerobic managed landfills under normal operating conditions
- Decay rate constant ( $k$ ): the rate at which methane is generated by anaerobic decomposition of waste in the FOD calculation. The  $k$  value for each waste material category is based on the waste half-life - the time it takes for  $DOC$  in the waste to decay to one-half its initial mass. The decay rate constant is primarily influenced by moisture content, but nutrient availability, temperature and pH can also affect the value of  $k$ . The precipitation-based material-specific decay rates are based largely on the decay rates from the British Columbia *LFG Generation Assessment Procedure Guidelines* (BC MOE 2009) for five precipitation zones and align with the decay rates used in the NIR that distinguish rapidly degrading, moderately degrading, and slowly degrading materials. IPCC-based decay rates are identical to those used in the NIR for “wet” and “dry” climate zones. The decay rates used in the model are provided in Appendices A2 and A3

## First-order decay equations

The following calculations are repeated for each waste material category and for each year in the Modelling Tool. The equations used are consistent with the methodology described in Volume 5, Chapter 3 of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006), and in the *National Inventory Report* (ECCC 2025b).

1. Of the waste deposited in an inventory year  $T$ , determine the mass of decomposable degradable organic carbon ( $DDOCmd_T$ ).  $DDOCmd_T$  is the fraction of waste deposited in a given year that can decompose to generate methane.

*Equation 2. Mass of decomposable DOC (Equation 3.2, p. 3.9, in IPCC 2006)*

$$DDOCmd_T = W \times DOC \times DOC_f \times MCF$$

where		Units
$DDOCmd_T$	= Mass of decomposable <i>DOC</i> deposited in year $T$	tonnes
$W$	= Mass of waste material deposited in year $T$	tonnes
$DOC$	= Fraction of degradable organic carbon in the waste	fraction
$DOC_f$	= Fraction of <i>DOC</i> that can decompose under anaerobic conditions	fraction
$MCF$	= Methane correction factor (assumed value of 1)	fraction

2. Determine how much decomposable degradable organic carbon has accumulated by the end of the inventory year  $T$  ( $DDOCma_T$ ). This will include the quantity that was deposited in the year  $T$  as well as the quantity that has not yet decomposed from previous years.

*Equation 3. Mass of DDOC accumulated in landfill at the end of year  $T$  (Equation 3.4, p. 3.9, in IPCC 2006)*

$$DDOCma_T = DDOCmd_T + (DDOCma_{T-1} \times e^{-k})$$

where		Units
$DDOCma_T$	= Mass of <i>DDOC</i> accumulated in landfill at the end of year $T$	tonnes
$DDOCmd_T$	= Mass of <i>DDOC</i> deposited in landfill in the year $T$	tonnes
$DDOCma_{T-1}$	= Mass of <i>DDOC</i> accumulated in landfill at the end of year $T-1$	tonnes
$k$	= Decay rate constant	years <sup>-1</sup>

3. Determine how much decomposable degradable organic carbon has decomposed in the landfill in the inventory year  $T$  ( $DDOCm,decomp_T$ ).

*Equation 4. Mass of DDOC decomposed in the landfill in year  $T$  (Equation 3.5, p. 3.9, in IPCC 2006)*

$$DDOCm,decomp_T = DDOCma_{T-1} \times (1 - e^{-k})$$

where		Units
$DDOCm,decomp_T$	= Mass of <i>DDOCm</i> decomposed in the landfill in year $T$	tonnes
$DDOCma_{T-1}$	= Mass of <i>DDOC</i> accumulated in landfill at the end of year $T-1$	tonnes
$k$	= Decay rate constant	years <sup>-1</sup>

4. Determine the mass of methane generated in the inventory year  $T$  due to the degradation of the degradable organic carbon that has decomposed in the year  $T$ .

*Equation 5. Methane generated in year  $T$  (Equation 3.6, p. 3.10, in IPCC 2006)*

$$CH_4gen_T = DDOCm,decomp_T \times (F_{CH_4} \times \frac{16}{12})$$

where		Units
$CH_4gen_T$	= Methane generated in year $T$	tonnes
$DDOCm,decomp_T$	= Mass of <i>DDOCm</i> decomposed in the landfill in year $T$	tonnes
$F_{CH_4}$	= Fraction of methane, by volume, in generated LFG (assumed 0.5)	fraction
$\frac{16}{12}$	= Molecular weight ratio of $CH_4/C$	ratio

## 2.3 Instructions for using the ECCC Landfill Methane Modelling Tool

The following subsections describe the user inputs and options in the ECCC Landfill Methane Modelling Tool and guidance around selection of appropriate modelling parameters.

The federal *Landfill Methane Regulations* require certain landfills to calculate the annual methane generation rate using the ECCC Landfill Methane Modelling Tool (4(1)(a)).

### Landfill information

The first section of the Modelling Tool's 'INPUT' worksheet requires the user to enter the following information regarding the location and operating status of the landfill:

- Landfill name
- Province in which the landfill is located
- Landfill opening year (the first year the landfill began receiving waste)
- Landfill closing year (the last year in which the landfill received waste, either a known year for closed landfills or estimated for active landfills)

The earliest possible opening year in the model is 1941. The landfill location determines which provincial or territorial waste composition default values will be used in the model.

### Model Parameters

The user must select the basis for determining material-specific decay rates (k): based on either average annual precipitation or the IPCC climate zone (wet or dry). Decay rates based on climate zone align with the current approach used in ECCC’s NIR where landfill methane generation is modelled on a regional basis (i.e. not location specific). Decay rates based on average annual precipitation offer an opportunity for more location specific parameters to be used. The Modelling Tool does not allow the user to input specific decay rates.

#### *Decay rates based on average annual precipitation*

If “average annual precipitation” or “average annual precipitation with leachate recirculation” is selected, the user is required to enter a site-specific value for average total annual precipitation (in mm per year). The user can obtain average annual precipitation amounts measured at the nearest meteorological station from the [Canadian Climate Normals \(1991 to 2020\) database](#) (ECCC 2025a).

For landfills that recirculate collected leachate into the waste mass, the user is required to input information on the quantity of leachate recirculated (in litres per year) and the landfill area receiving the leachate (in m<sup>2</sup>). The model will automatically adjust the annual precipitation amount using the calculation shown in Equation 6.

*Equation 6. Calculation of annual precipitation adjusted for leachate recirculation*

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$$AAP_{adjusted} = AAP + \left( \frac{ALR}{LFA} \right)$$

where		Units
$AAP_{adjusted}$	= Average annual precipitation adjusted for leachate recirculation	mm/year
$AAP$	= Average annual precipitation	mm/year
$ALR$	= Average annual leachate recirculated	litres/year
$LFA$	= Landfill area within the effective radius of leachate recirculation	m <sup>2</sup>

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Based on the data entered for average annual precipitation and leachate recirculation, the “decay rate precipitation category” (precipitation range) is automatically populated. The decay rate precipitation ranges are as follows:

- <250 mm/year
- 250 to 500 mm/year
- >500 to 1000 mm/year
- >1000 to 2000 mm/year
- >2000 mm/year

### ***Decay rates based on climate zone***

If the “IPCC climate zone” option is selected as the basis for determining decay rates, the Modelling Tool will use the material-specific decay rates which are based on the IPCC Guidelines for the boreal-temperate wet or dry climate zones (IPCC 2006) and extended to other waste materials based on ECCC analyses. The “wet” and “dry” climate zones are defined by the ratio of mean annual precipitation to potential evapotranspiration: wet climates have a mean annual precipitation that is greater than the potential evapotranspiration, while dry climates have a mean annual precipitation that is less than the potential evapotranspiration. Determination of “wet” and “dry” climate zones used in the NIR is based on the long-term mean annual precipitation and mean annual potential evapotranspiration between 1941 and 2024 (University of East Anglia and Met Office 2025).

A link to an ECCC map of wet and dry climate zones used in the NIR is provided with the Modelling Tool to help the user identify the appropriate zone for the landfill location.

The complete list of climate zone-based decay rates is provided in Appendix A3.

### **Annual waste disposal**

The annual quantity of MSW, wastewater sludge/biosolids and soil deposited in the landfill (in tonnes/year) is required to quantify methane generation. Before entering annual waste disposal data, the user must select one of the following two options for how the annual waste quantities will be entered:

- As bulk MSW – in this case province and territory-specific waste composition data representing bulk waste will be used to calculate quantities of waste materials landfilled
- By the sector of origin: Residential, Industrial/Commercial/ Institutional (ICI) and Construction and Demolition (C&D) waste – in this case provincial and territorial sector-specific waste composition data will be used to calculate quantities of waste materials landfilled

Once an approach is selected, the cells requiring input will be shaded green. In addition to the quantities of MSW, the user must enter annual quantities of sludge (wastewater sludge or biosolids) and soil (e.g. contaminated soil, but not including landfill cover material) disposed, as applicable. Biosolids should be entered as wet weight.

To estimate methane generation for a given year, the user must enter the quantities of waste disposed for each year the landfill accepted waste up to, and including, that year. Where an estimate of future methane generation is of interest, users can enter estimated future quantities of waste disposed until the anticipated closure year is reached.

For years where detailed disposal data is not available (for example, prior to the installation of weigh scales at the landfill), the annual waste tonnage received should be estimated considering the following recommended approaches:

- Multiply the estimated population served by the landfill in each year by an appropriate per capita waste disposal rate. The per capita disposal rate may be based on existing landfill-specific waste disposal and population data (for a year where this data is available). Provincial/territorial per capita waste disposal rates may also be used, if available.
- Use any available estimates of total waste disposed ("waste-in-place") for specific years in the landfill's history (for example, based on a topographic or aerial survey). The difference between any two waste-in-place values can be distributed across the intervening years evenly (or based on other assumptions). If the waste-in-place data is in volumetric units (e.g. cubic metres), an appropriate waste density value (based on the procedures employed at the landfill including compaction, cover material, cover frequency, etc.) should be used to estimate the waste mass in tonnes.
- Extrapolate the waste quantity for the first year for which waste quantities are available backwards in time to the landfill's opening year.

### Waste composition data

The Landfill Methane Modelling Tool calculates the quantity (in tonnes) of each waste material disposed for each year of operation based on the annual waste disposal data entered and default waste composition data. The default waste composition data included in the model has been compiled by ECCC from waste characterization studies as described in the NIR (ECCC 2025b).

The waste material categories included in the ECCC Landfill Methane Modelling Tool are summarized in Table 1 and category descriptions are provided in Appendix A4.

*Table 1. Waste material categories in ECCC Landfill Methane Modelling Tool*

<b>Decomposable waste (generating methane)</b>	<b>Inert waste (not generating methane)</b>
• Food	• Plastics
• Paper	• Metals
• Soiled paper	• Glass
• Wood	• Household hazardous waste
• Yard and garden	• Concrete
• Diapers and sanitary	• Asphalt
• Pet waste	• Electronics
• Rubber and leather	• Ash
• Textiles	• Rubber
• Soil	• Inert construction debris
• Sludge	• Other – C&D (sector-specific waste)
• Other – Residential (sector-specific waste)	
• Other – ICI (sector-specific waste)	
• Other – Unknown (bulk waste)	

Since they are assumed to be non-decomposable, the total annual quantity of inert waste materials (as listed above) is accounted for in the overall waste composition in the model but is not included in the calculation of methane generation.

### ***Using site-specific waste composition data***

If site-specific bulk waste composition data is available, the user may enter it into the tool by selecting “yes” in response to the relevant question under Annual Waste Disposal on the ‘INPUT’ worksheet. This functionality is only available when the user is modeling “Bulk MSW” quantities (i.e. when “Sector of origin” quantities of waste are entered, the model uses only default waste composition data for each sector).

The user-defined data is entered in the ‘WASTE COMPOSITION’ worksheet. The worksheet is pre-populated with the default bulk waste composition described above, which can be referenced for years in which user-defined data is not available. It is important to confirm that values are entered for all years and waste materials and that the total of all the waste composition percentages equals 100% for each year.

### **Diversion of biodegradable waste**

The tool includes an option to model the impact of future biodegradable waste diversion on methane generation. The user can indicate whether the model should include this analysis on the ‘INPUT’ worksheet, by selecting “yes” in the drop-down menu. If selected, input fields in the ‘DIVERSION’ worksheet will be visible and available for input. If the user selects “no”, input fields in the ‘DIVERSION’ worksheet will not be visible and the user proceeds to the ‘RESULTS’ worksheet.

In the ‘DIVERSION’ worksheet, the user enters annual quantities of biodegradable waste material that will be diverted from the landfill for future years, either by mass (tonnes) or as a percentage (%) of the calculated annual quantity of the waste material that would be disposed each year. Diverted biodegradable waste is entered by waste category (Food, Soiled paper, Yard and garden, Paper, Wood, Diapers and sanitary, Pet waste and Textiles). The resulting quantity of each material type included in the model is shown.

### **Model results**

The ‘RESULTS’ worksheet displays the estimated annual methane generation from the landfill opening year until 2075. Results are displayed in a graph that plots the annual methane generation, and in a table that provides annual quantities (in tonnes) of estimated methane generation.

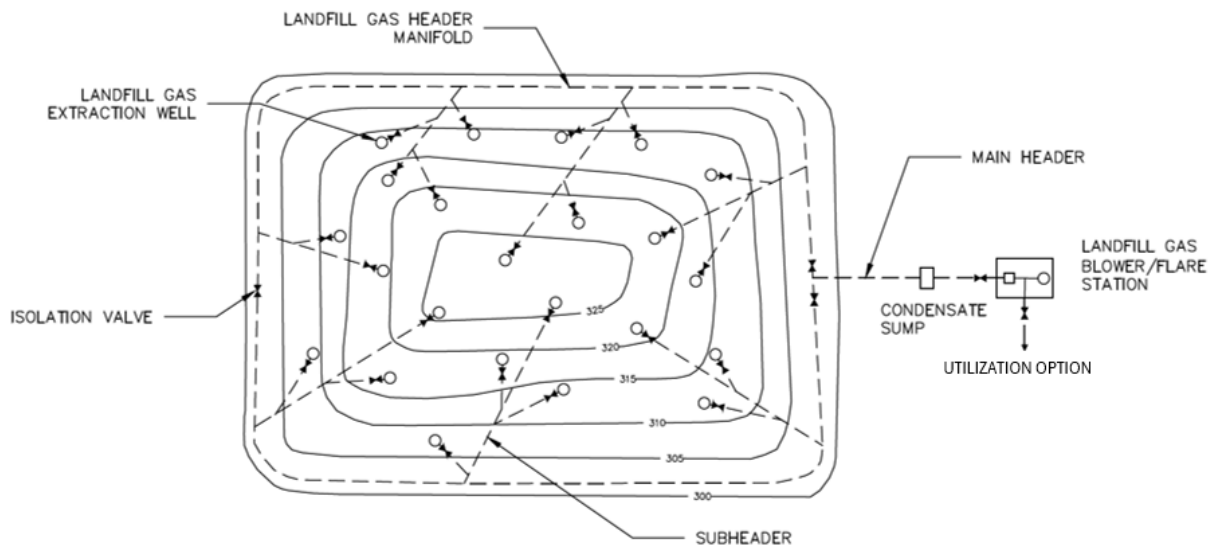
If the user chooses to use the optional diversion function, the graph and table will show methane generation for future years both with and without the biodegradable waste diversion. This allows the user to compare the impact of future biodegradable waste diversion programs with a baseline scenario.

### **Model parameters**

The ‘MODEL PARAMETERS’ worksheet provides the values for decay rates (k), DOC and DOC<sub>f</sub> that are used in the model. The decay rates shown include the values available for each precipitation or climate zone.

### 3. Monitoring methane recovery

Methane emissions can be controlled at landfills by installing infrastructure to recover LFG before it can be emitted to the atmosphere. LFG recovery (or collection) systems typically consist of a network of vertical recovery wells and horizontal collectors/headers connected to blowers, which create negative pressure conditions within the waste mass and collect LFG. Recovered LFG is either combusted in flares or utilization systems (boilers for heating, engines/turbines for power generation) or can be upgraded to renewable natural gas. The layout of a typical LFG recovery system is shown in Figure 1.



*Figure 1. Example of general layout of a landfill gas recovery system*

Monitoring of the LFG recovery system is carried out in order to characterize the LFG, optimize performance, minimize air intrusion in the system and reduce the amount of time a system is taken down for repair. As part of this monitoring, the quantity of methane recovered by the system is determined and used to confirm emission reductions, to estimate potential fugitive emissions, and for comparison with methane generation modelling estimates.

Methane recovery may be reported for various reasons, including in annual landfill monitoring and operating reports, for LFG regulatory reporting requirements, in GHG or carbon offset credit Measurement, Reporting and Verification (MRV) reports and for government data requests (such as the ECCC biannual landfill methane survey).

The federal *Landfill Methane Regulations* require:

- Measurement of the methane concentration in recovered LFG conveyed to each destruction or energy recovery device or treatment system (flare, turbine, engine, gas treatment system, biofilter, etc.), either at an aggregate monitoring location or at individual monitoring locations, at least monthly (8(4)(a))
- Measurement of the volumetric flowrate of recovered LFG at each device or system, at least every 15 minutes (8(4)(b))
- Records of the volume of landfill gas conveyed each day to each device or system (9(d))
- Reporting of the quantity of methane, in tonnes, conveyed each year to each device or system (22(j))

### 3.1 Landfill gas recovery system monitoring

#### Instrumentation

Quantifying landfill methane recovery requires instrumentation that measures both the flow rate and the methane concentration of the LFG collected by the recovery system. This equipment records gas composition, gas flow rate, and the total volume of gas recovered at a regular frequency (for example, by minute, hour, day, month, or year). This allows for the flow to be measured and monitored at single points in time and over set intervals to provide accurate cumulative readings. Sensors for temperature and pressure may be included in the instrumentation configuration, where required, to support conversion of measured gas flow to standard conditions.

#### *Gas flow meter*

The LFG recovery system should include permanent flow meters that continuously measure the flow rate of LFG delivered to each destruction or utilization device. Thermal mass flow meters are the most commonly used device for measuring flow rate and the total accumulated volume of LFG recovered. Such units provide the flow and volumetric readings at standard temperature and pressure without the need for separate temperature and pressure measurement equipment.

Other flow measurement instruments, including differential pressure and turbine meters, can also effectively read gas flow in a pipe, but may not be suitable for low flow rates. In addition, these instruments are less effective under the lower-pressure gas conditions associated with LFG systems and introduce a further pressure drop in the system. Changing an existing flow meter for a new thermal mass flow meter may not be necessary, provided that the unit accuracy and reliability are equal to or better than a thermal mass flow meter and that readings can be automatically or manually converted to standard temperature and pressure.

#### *Gas analyzer*

Gas analyzers measure the methane concentration within the recovered LFG and can be portable or permanent (integrated). Gas composition data is typically collected and recorded before thermal destruction or end-use. For a project with multiple destruction or utilization devices, if the LFG is delivered to the devices from a common manifold or header upstream of the devices, one gas analyzer can be placed to measure the methane content of the LFG at that common manifold or header pipe. If the LFG is delivered to each device from separate manifolds or header pipes, a separate gas analyzer is required upstream of each individual device.

The most common gas analyzers for recovery system monitoring incorporate non-dispersive infrared (NDIR) sensors for measuring methane and carbon dioxide percent by volume and electrochemical sensors for measuring oxygen percent by volume. The units are calibrated to measure a volumetric fraction of each of these components (with the balance gas assumed primarily to be nitrogen, along with other trace compounds). Trace contaminants, such as hydrogen sulphide and carbon monoxide, can also be measured using electrochemical sensors incorporated into the gas analyzer. Portable gas analyzers may also be used for regular, non-continuous recovery system monitoring at the blower or at destruction/utilization devices, unless regulatory or other reporting programs require continuous monitoring.

### ***Temperature and pressure gauges***

If the flow meter does not automatically correct the LFG volume to standard conditions, temperature and pressure must be measured using separate temperature and pressure instrumentation at the same measurement frequency as the LFG volumes. If the flow meter automatically corrects the LFG volume to standard temperature and pressure conditions, no additional temperature and pressure gauges are required.

### ***Data collection***

The flow meter (and gas analyzer, if a permanent, continuous-monitoring instrument is used) should have a transmitting feature for data to be recorded and continuously logged via the blower or flare station programmable logic controller (PLC) and human-machine interface.

The LFG recovery system operating hours, downtime, and offline hours for routine or non-routine maintenance should also be tracked and recorded through the facility data logging system, including the PLC and supervisory control and data acquisition (SCADA) systems.

### ***Instrument configuration***

The flow meters and gas analyzers should be installed and configured to measure gas flow rates and methane content before the introduction of any supplemental fuel for the flare. The flow meter and the gas analyzer sampling points are located at the blower station on the downstream (pressurized) side of the recovery system blowers and upstream of the thermal combustion or utilization devices. The typical locations of flow meters, gas analyzers and sampling ports are shown in Figure 2.

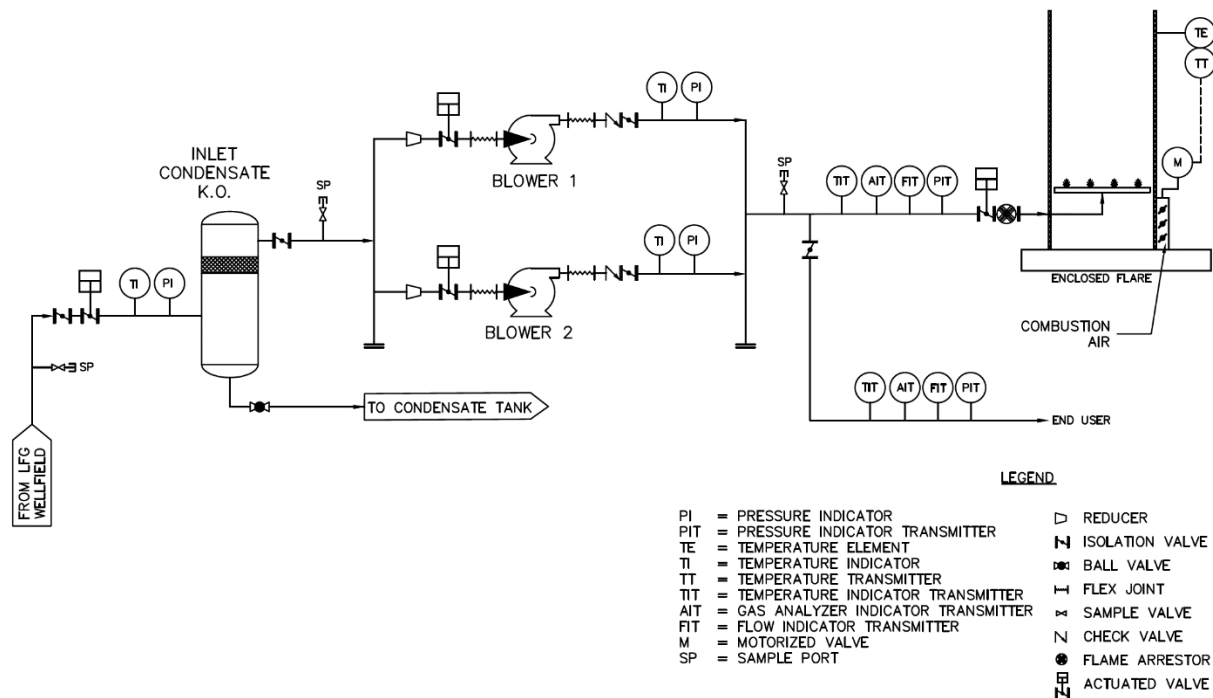


Figure 2. Typical landfill gas recovery system monitoring locations

LFG volume, temperature, pressure and methane content should be measured under the same conditions - on either a wet or dry basis. No devices or equipment that could result in a change in the LFG composition by volume should separate a gas analyzer and a flow meter.

### Instrument Quality Assurance and Quality Control

Quality Assurance and Quality Control procedures should be implemented for LFG flow meters and gas analyzers, including the following:

- Operators should confirm the gas analyzer is installed in accordance with the manufacturer's instructions to ensure the concentration measurements are accurately recorded within the equipment calibration range
- Equipment is calibrated (factory or on-site calibration, in accordance with manufacturer requirements) at the time of installation and prior to use
- Landfill operators should confirm the gas analyzer is calibrated at least annually or in accordance with the manufacturer's recommendations or as specified in regulatory/reporting requirements (whichever is more frequent) and that calibration records are documented
- At least annually, flow meters should be checked for accuracy by a qualified third party, either using a portable instrument, such as a pitot tube, or by following the manufacturer's specifications, and the percentage drift recorded. Operators may require one or more spare flow meters to serve as replacements during periodic off-site calibration, if necessary
- Equipment should be cleaned and inspected in accordance with the manufacturer's specifications

The LFG flow meter and gas analyzer calibration accuracy should show that these measurement instruments provide a reading of volumetric LFG flowrate and methane content that is within a 10% accuracy threshold.

When the instrument shows a shift outside the ±10% accuracy threshold, appropriate corrective action(s) should be taken, in accordance with the manufacturer’s specifications and the instrument should be rechecked for measurement accuracy. If the instrument is still out of the ± 10% accuracy threshold, the instrument should be calibrated by the manufacturer or by a third party certified for that purpose by the manufacturer.

### Correction for temperature and pressure

If the flow meter does not automatically correct the measured volumetric flow rate to standard temperature and pressure, the corrected volume should be calculated following Equation 7. The reference pressure should be 101.325 kPa (1 atm), and the reference temperature should be based on reporting requirements, if available, or chosen from Table 2. The reference temperature and pressure and the corresponding methane density (as set out in Table 2) should be applied consistently to ensure accurate volume and mass calculations.

Table 2. Methane density at reference temperature and pressure

Reference Pressure (kPa)	Reference Pressure (atm)	Reference Temperature		Density of CH <sub>4</sub> (kg/m <sup>3</sup> )
		°C	K	
101.325	1	0	273.15	0.716
101.325	1	5	278.15	0.703
101.325	1	10	283.15	0.691
101.325	1	15	288.15	0.679
101.325	1	20	293.15	0.667
101.325	1	25	298.15	0.656

Equation 7. Quantity of LFG sent to each destruction or utilization device, corrected for temperature and pressure

$$LFG_{COR} = LFG_{UC} \times \frac{T_{ref}}{T_m} \times \frac{P_m}{101.325}$$

where		Units
$LFG_{COR}$	= Corrected volume of recovered LFG	m <sup>3</sup> LFG
$LFG_{UC}$	= Uncorrected volume of recovered LFG	m <sup>3</sup> LFG
$T_{ref}$	= Reference temperature of the recovered LFG, as set out in Table 2	K
$T_m$	= Measured temperature of the recovered LFG	K
$P_m$	= Measured pressure of the recovered LFG	kPa
101.325	= Reference pressure of the recovered LFG	kPa

## Data review

Data collected from the gas flow meters and gas analyzers should be reviewed for errors and trends that may indicate inaccurate data. If gas is utilized, monthly recovery system and utilization system metered flow rates and recorded methane concentrations can be compared for potential accuracy variations.

## 3.2 Calculating methane recovery

Where not automatically provided by the data logging software, the quantity of recovered methane should be calculated at the same frequency as the recorded methane concentration data. The total volume of recovered LFG reported in standard cubic metres (m<sup>3</sup>) over a specified time interval is combined with the average methane concentration for that interval to calculate the volume of methane recovered. The length of the time interval should correspond to the measurement frequency and comply with recording requirements specified by regulatory or other reporting programs.

For example, Equation 8 is used to calculate the volume of recovered methane over a specified time interval of one day at a specific monitoring location.

*Equation 8. Daily volume of recovered methane*

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$$Q_{CH_4\text{daily}} = LFG_{vol} \times \%CH_4\text{average}$$

where		Units
$Q_{CH_4\text{daily}}$	= Volume of methane recovered in a day	m <sup>3</sup> CH <sub>4</sub>
$LFG_{vol}$	= Cumulative volume of recovered LFG, measured at standard temperature and pressure, during the day	m <sup>3</sup> LFG
$\%CH_4\text{average}$	= Average methane concentration (percent by volume in the LFG) recorded during the day	%

---

The annual quantity of methane delivered to each destruction/utilization device is calculated by summing all calculated or recorded methane recovery volumes from each time interval in a calendar year and converting volume to mass using the following equation:

Equation 9. Annual mass of recovered methane per device

$$CH_4 \text{ device} = \sum_{t=1}^n (Q_{CH_4,t}) \times (\rho_{CH_4} \times 0.001)$$

where		Units
$CH_4 \text{ device}$	= Mass of CH <sub>4</sub> delivered to destruction/utilization device during a calendar year	tonnes CH <sub>4</sub>
$Q_{CH_4,t}$	= Total volume of CH <sub>4</sub> sent to destruction/ utilization device during measurement period, t	m <sup>3</sup> CH <sub>4</sub>
$\rho_{CH_4}$	= Density of CH <sub>4</sub> , as set out in Table 2	kg CH <sub>4</sub> /m <sup>3</sup> CH <sub>4</sub>
0.001	Conversion factor, kilograms to tonnes	t CH <sub>4</sub> /kg CH <sub>4</sub>
n	Number of measurement periods in a calendar year	-
t	Measurement period	-

The total annual mass of methane recovered by the LFG recovery system is calculated as the total of the methane quantities recovered by each destruction/utilization device.

Equation 10. Total annual mass of methane recovered by the LFG recovery system

$$CH_4 \text{ recovered} = \sum_{i=1}^n CH_4 \text{ device},i$$

where		Units
$CH_4 \text{ recovered}$	= Total mass of CH <sub>4</sub> recovered by LFG recovery system	tonnes CH <sub>4</sub>
$CH_4 \text{ device},i$	= Mass of CH <sub>4</sub> delivered to destruction/utilization device during a calendar year	tonnes CH <sub>4</sub>
n	Number of destruction or utilization devices	-
i	Destruction or utilization device	-

### 3.3 Calculating collection efficiency

Collection efficiency is a measure of the effectiveness of the gas recovery system in recovering the methane generated in the landfill. The collection efficiency is the ratio of the methane recovered by the LFG recovery system to the total amount of methane generated in the landfill.

The efficiency of LFG recovery systems is influenced by a number of factors, including:

- operational status of landfill (open or closed)
- extent and type of landfill cover system (including cover materials, thickness, and integrity)

- proportion of the landfill area with gas recovery infrastructure installed
- LFG recovery well area of influence
- LFG recovery system design and operation (including optimized gas recovery wells, system outages, elevated leachate levels in recovery wells)

The collection efficiency using measured methane recovery data from the LFG recovery system and the modelled annual methane generation is calculated as follows:

*Equation 11. Calculated collection efficiency based on modelled methane generation and measured methane recovery data*

---


$$CE_{calculated} = \frac{CH_4_{recovered}}{CH_4_{generated}} \times 100$$

where		Units
$CE_{calculated}$	= Calculated collection efficiency	%
$CH_4_{recovered}$	= Total mass of CH <sub>4</sub> recovered by LFG recovery system (see Equation 10)	tonnes CH <sub>4</sub>
$CH_4_{generated}$	= Total mass of CH <sub>4</sub> generated at the landfill by waste decomposition (see Section 2)	tonnes CH <sub>4</sub>

---

Collection efficiency is estimated to typically range between 60 and 95% on an annual basis. The British Columbia design guidelines for LFG management facilities specify a performance objective of at least 75% collection efficiency for LFG recovery systems (BC MOE 2010). Given the uncertainty related to the estimated methane generation, comparison of calculated collection efficiencies to determine performance may be challenging; however, comparison of calculated collection efficiencies over time may provide an indication of the impact of, or need for, system improvements.

## 4. Landfill gas wellfield monitoring

Regular monitoring and adjustment of the recovery system wellfield is necessary to balance the system and optimize LFG recovery. The LFG generation rate will vary over time, and the LFG flow rate at each well may require adjustment to not over- or under-draw from the wellfield. Improper balancing of the wellfield can result in elevated methane emissions or air intrusion, which can disrupt anaerobic decomposition or cause subsurface fires. Wellfield monitoring can also help to identify operational issues such as flooded extraction wells and damaged wellhead components that have the potential to cause methane leaks.

Data collected at each individual LFG recovery well during each monitoring round typically include:

- gas composition (percent by volume) – methane, carbon dioxide, oxygen, and balance gas
- vacuum pressure – mm of water column (or inches of water column)
- flow rate – standard m<sup>3</sup>/h (or standard cubic feet per minute [ft<sup>3</sup>/min])
- gas temperature – °C (or degrees Fahrenheit [°F])

Typically, recovery system wellfield surveys (monitoring at each individual LFG recovery well) are conducted monthly, but may be implemented more frequently to attain an optimum methane concentration at a maximum sustainable flow rate, particularly where required for energy generation projects. The objective of the monitoring and adjustments is to maintain CH<sub>4</sub>, CO<sub>2</sub>, O<sub>2</sub>, and N<sub>2</sub> (balance gas) concentrations and temperature within acceptable ranges and to ensure vacuum pressure.

Some provinces have established performance standards for oxygen and nitrogen concentrations in LFG extraction wells:

- The BC performance standard requires that oxygen and nitrogen contents not exceed 2.5% and 15% by volume, respectively, at a LFG extraction [recovery] well (BC MOE 2010)
- The Québec landfill regulation requires the concentrations of oxygen or nitrogen to be respectively less than 5% and 20% by volume in each drain and wet well in the system (Québec 2005)

Although the normal temperature at landfills may vary, temperature readings above 55 degrees Celsius (131 degrees Fahrenheit) may be indicative of elevated temperatures within the waste mass and may require investigation (Krause 2022).

The control valves on the wellheads are used to adjust (increase/decrease) vacuum applied to each well to maintain a sustainable flow. Gas readings (specifically vacuum pressure and flow rate) are taken before and after wellhead flow rate adjustments; however, it will typically take some time for changes in gas composition concentrations to stabilize.

The approach to making wellfield adjustments should include consideration of historical data trends and may require professional judgement based on site-specific experience.

The federal *Landfill Methane Regulations* require monthly monitoring of LFG recovery wells for:

- gauge pressure (to check for levels above 0.5 inches of water) (10(1)(a)(i))
- oxygen concentration (to check for concentrations higher than 5% by volume) (10(1)(a)(ii))
- LFG flow rate (to check for conditions of zero volumetric flow rate) (10(1)(a)(iii))
- damaged equipment components (10(1)(b))

If any of the first three conditions above are identified, before or during the next monthly monitoring round:

- measurements must be taken to demonstrate that the conditions no longer exist (11(1)(a)) or
- the recovery well and its cover penetration must be inspected for elevated methane concentrations using the methods described in Section 5.1 of this document (for wellhead equipment) and Section 6.3 of this document (for cover penetrations) (11(1)(b)).

If damaged equipment components are identified, the recovery well and its cover penetration must be inspected for elevated methane concentrations as described above (11(2)).

Monthly monitoring is not required at a LFG recovery well that (10(3)(a)):

- is not in operation due to construction activities, including repairs or modifications to the well, the active landfill gas recovery system, the leachate collection system or the landfill cover
- is not in operation due to measures taken to extinguish or prevent a fire at the landfill
- has been decommissioned or has not operated in the previous 30 days
- has no accessible location for measurements to be taken
- is located in a portion of the landfill that is under final cover and in which the methane concentration in LFG is below 25% by volume in six consecutive monthly measurements

If a LFG recovery well is instrumented with equipment that continuously monitors gauge pressure, oxygen concentration and volumetric flow rate and automatically adjusts the pressure in the well, the well does not require monthly manual monitoring of these parameters. It must still be inspected monthly for damaged equipment components (10(3)(b)).

## 4.1 Instrumentation

Most portable handheld field instruments combine infrared gas analyzers for CH<sub>4</sub> and CO<sub>2</sub> measurement with an electrochemical cell for O<sub>2</sub> measurement, and calculate N<sub>2</sub> (balance gas) concentration. Commonly used instruments can also measure static and differential pressure, gas flow rate and temperature.

If separate instruments are being used for gas composition and pressure/flow, the pressure measurements should be completed first, as extracting the gas sample may affect the gas pressure. Gas pressure can be measured with a Magnehelic pressure gauge, a handheld manometer or an electronic pressure gauge.

Landfill gas flow is often measured using an orifice plate inserted cross-sectionally into the gas header line between two flanges. A pressure measurement is taken at monitoring ports installed on either side of the orifice plate to determine the pressure differential, and the gas flow is calculated from the gas equation. Other options for measuring flow may include pitot tubes, thermal anemometers, mass

flowmeters and venturi tubes. Pitot tubes or orifice plates may be built into pre-fabricated LFG recovery wellheads.

Figure 3 depicts a typical LFG recovery well and wellhead assembly with sampling ports for measuring gas composition, flow rate, temperature and vacuum pressure.

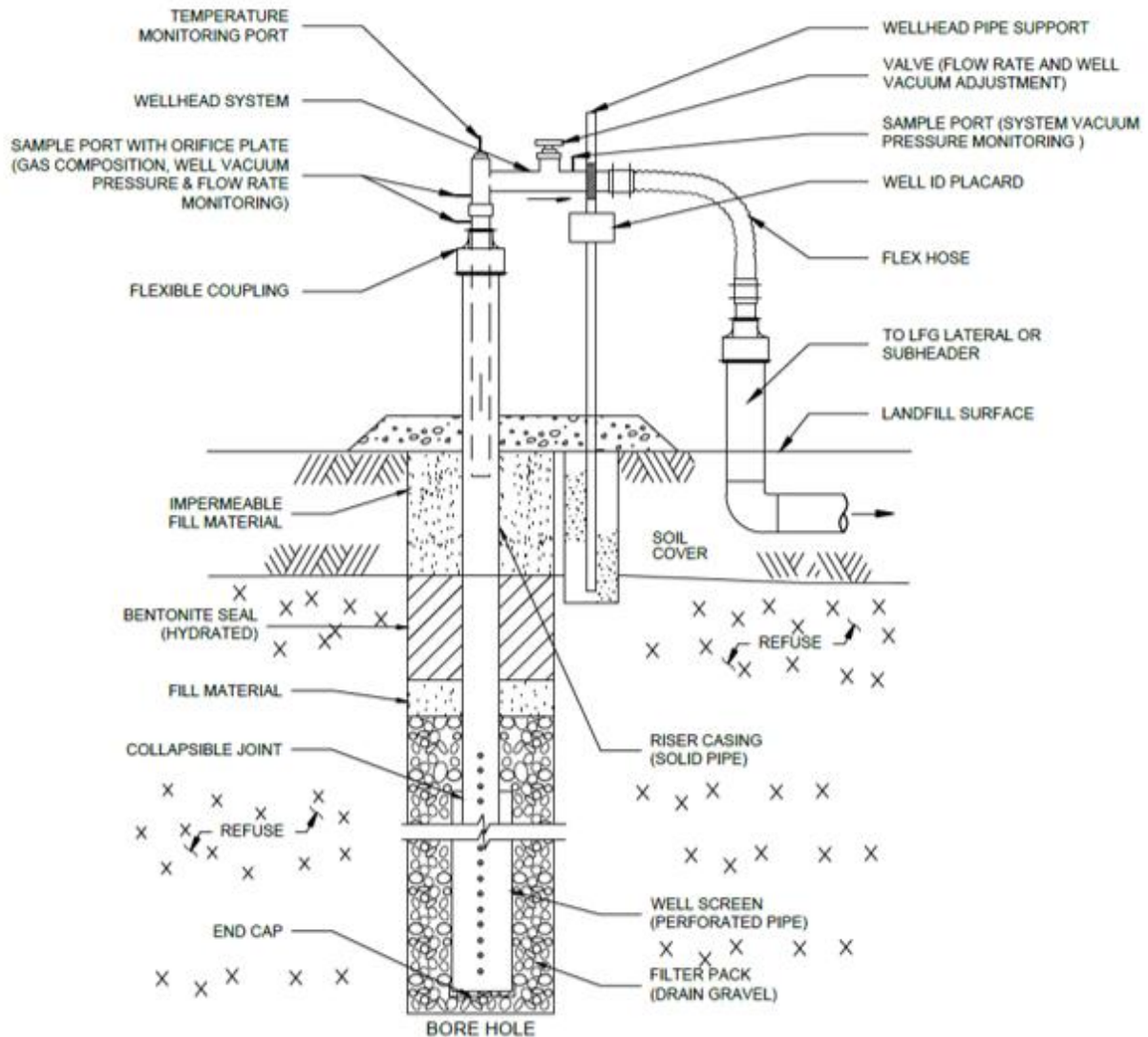


Figure 3. Typical landfill gas recovery wellhead assembly

Under an alternative approach to wellfield tuning, LFG recovery wellheads are instrumented with sensors that continuously monitor landfill gas quality, flow pressure and temperature. This data is relayed to a server where an algorithm determines optimal valve positions for wells across the wellfield and adjusts them. The wells can be continuously tuned and optimized. While automated systems will typically have a higher capital cost compared to conducting manual wellfield surveys, the improved recovery system efficiency and gas quality control may warrant the use of an automated wellfield control system.

## 4.2 Recommended documentation

In general, all measurements collected during wellfield monitoring should be recorded, including initial readings and measurements following any wellfield adjustments, as well as specific observations and notes regarding actions required for future reference. If using a portable handheld analyzer, data should be stored and downloaded for review and evaluation, and retained for operational records.

The wellfield monitoring record should also include the following information:

- Atmospheric conditions (temperature, barometric pressure)
- Site-specific conditions (including snow cover, wet or dry conditions)
- Equipment used
- Calibration dates for all monitoring instrumentation

Parameters measured at the blower station (gas composition, system vacuum, flowrate) should also be recorded during wellfield monitoring for review and comparison before and after wellfield system adjustments.

The federal *Landfill Methane Regulations* require that the following records be maintained for each wellhead monitoring event:

- The well location, well identifier and monitoring date (12(a))
- The gauge pressure, oxygen concentration and volumetric flow rate measured at each well (12(a))
- If applicable, the reason(s) that measurements were not collected (12(a)) (i.e. which of the circumstances described in 10(3) exist: well is not in operation due to construction activities or due to measures to extinguish or prevent a fire; well is decommissioned; wellhead is inaccessible; low methane content; or wellhead is equipped with a continuous monitoring system)

## 5. Equipment leak detection

The infrastructure installed to collect and convey LFG to destruction or utilization devices may become a source of methane emissions, due to leaks from equipment components such as connections, fitting, valves, and seals. Equipment leaks may be due to component deterioration, improper installation, or loosening due to vibration. Leak detection and repair (LDAR) protocols should be developed for landfill gas management systems in order to promptly identify and mitigate methane leaks. Leak repair may include tightening or replacing fasteners, cleaning or replacing gaskets and seals, or replacing equipment components.

There are currently no provincial requirements for methane leak detection surveys on landfill gas equipment.

The federal *Landfill Methane Regulations* require leak detection surveys on all equipment components containing LFG three times per year, with at least 60 days between surveys. The surveys must be carried out in accordance with US EPA Method 21 ((13(1)(a)).

An equipment component does not require monitoring if this would pose a serious risk to human health or safety (13(3)).

Although the *Landfill Methane Regulations* permit the use of alternative methane leak detection instruments and methods that are approved by the Minister (13(1)(b)), there are currently none approved. Alternative methods approved for use will be published in updates to this document.

A methane concentration at an equipment component of 500 parts per million by volume (ppmv) or greater is considered a methane leak.

As they are typically completed using the same type of instruments, equipment leak detection surveys and surface emission monitoring (Section 6) may be completed simultaneously.

### 5.1 US EPA Method 21

When applied to LFG infrastructure, US EPA Method 21 (US EPA 2017) requires the manual measurement of methane concentrations immediately adjacent to equipment components and establishes specifications for instruments as well as calibration and measurement methods.

#### Instrumentation

A handheld detector that measures volumetric methane concentrations (ppmv) is used for Method 21 leak detection surveys. The most common instrument for methane leak detection surveys is a flame ionization detector (FID).

The federal *Landfill Methane Regulations* include the following requirements for instrumentation, based on US EPA Method 21 (13(1)(a)).

An instrument meeting the following specifications is required:

- The instrument shall be capable of measuring 500 ppmv of methane with a resolution of 12.5 ppmv.

- The instrument shall be equipped with an electrically driven pump to ensure that a sample is provided to the detector at a constant flow rate. The nominal sample flow rate, as measured at the sample probe tip, shall be 0.10 to 3.0 l/min when the probe is fitted with a glass wool plug or filter that may be used to prevent plugging of the instrument.
- The instrument shall be equipped with a probe or probe extension not to exceed 6.4 mm in outside diameter, with a single end opening for admission of sample.

The following tests must be completed before the instrument is used each day:

- Calibration precision test. Make a total of three measurements by alternately using zero gas (less than 10 ppmv methane) and the specified calibration gas (500 ppmv of methane accurate to within 2 percent). Record the meter readings. Calculate the average algebraic difference between the meter readings and the known value. Divide this average difference by the known calibration value and multiply by 100 to express the resulting calibration precision as a percentage. The calibration precision shall be no more than 10 percent.
- Response time test. Introduce zero gas (less than 10 ppmv methane) into the instrument sample probe. When the meter reading has stabilized, switch quickly to the calibration gas (500 ppmv of methane). After switching, measure the time required to attain 450 ppmv (90 percent of the final stable reading of 500 ppmv). Perform this test sequence three times and calculate the average response time. The average instrument response time must be equal to or less than 30 seconds. The instrument pump, dilution probe (if any), sample probe, and probe filter that will be used during testing shall all be in place during the response time determination.

The instrument should be regularly calibrated by introducing calibration gas (500 ppmv of methane) into the instrument sample probe and adjusting the instrument meter readout to correspond to the calibration gas value. Depending on the instrument, this calibration may be done by the user or the manufacturer.

## Measurements and measurement locations

The federal *Landfill Methane Regulations* require that leak detection monitoring be completed on all equipment components that contain landfill gas (13(1)), including wells, pipes, flanges, fittings, valves, flame arrestors, knock-out drums, sampling ports, blowers, compressors, and connectors (1(1)). This includes components under positive, neutral or negative pressure.

Leak detection should be carried out with the probe inlet of the instrument held no more than 2 cm from the equipment component or no more than 5 cm from the surface of a vault containing equipment components. Specific steps are as follows:

- Place the probe inlet at the surface of the component interface where leakage could occur.
- Move the probe along the interface periphery while observing the instrument readout.
- If a reading of 200 ppmv of methane or more is observed, slowly sample the interface where leakage is indicated until the maximum meter reading is obtained.
- Leave the probe inlet at this maximum reading location for approximately two times the instrument response time.

Examples of the application of this general technique to specific equipment types can be found in Section 8.3.1 of Method 21 (US EPA 2017) (13(1)(a)).

## Documentation

The federal *Landfill Methane Regulations* require that the following records be maintained for leak detection monitoring:

- the date of the monitoring event and the name of the individual who conducted it (15(a))
- the type of each monitoring instrument used, including its make and model and the results of each calibration (15(b))
- any equipment component that was not monitored due to health and safety considerations (15(c))
- information on any detected methane leaks (concentrations of 500 ppmv or more) and associated follow-up activities (15(d))

## 5.2 Alternative methods

### Handheld TDLAS detectors

An emerging approach to methane leak detection at landfills is the use of handheld detectors that rely on Tunable Diode Laser Adsorption Spectroscopy (TDLAS) technology. This detector measures the path-integrated concentration of methane along a laser light beam's path between the detector and the target (equipment component), with methane concentrations measured in units of ppm-metre (ppm·m). Some handheld TDLAS detectors also incorporate optical gas imaging to allow visualization of methane leaks.

Leak detection using handheld TDLAS detectors can be performed more quickly than typical Method 21 surveys and at a distance of several metres from the components, which permits monitoring of inaccessible components.

### Other emerging methods

Other approaches that are being investigated for methane leak detection at landfills include airborne surveys and continuous monitoring systems. These methods are discussed in Section 7.

## 6. Measuring surface methane concentrations

This section describes surface emissions monitoring (SEM) surveys that measure methane concentrations at the landfill surface. SEM surveys can be undertaken at landfills with and without a LFG recovery system. The objective of measuring surface methane concentrations is to identify and locate fugitive emissions through landfill cover materials (“hot spots”) or at cover system penetrations. Once fugitive emissions have been identified, corrective measures can be undertaken to reduce or eliminate those emissions.

There are several methods and technologies that can be used for SEM surveys at landfills, some of which measure point concentrations at the location of the sensor or sampling inlet, while others measure path-integrated concentrations - the amount of methane present within the air column between the sensor and the ground surface. While these measurements may be used in approaches to estimate total site-wide emissions, the methods described in this section are used to identify localized areas of elevated methane concentrations.

The federal *Landfill Methane Regulations* require measurement of surface methane concentrations three times per year in areas of the landfill that have not received waste in the previous 12 months to identify exceedances of surface methane concentration thresholds of 500 ppmv (in a single location) or 25 ppmv (“zone-average” – the average of surface methane concentrations in zones of approximately 4,500 m<sup>2</sup>).

Under Québec’s *Regulation Respecting the Landfilling and Incineration of Residual Materials*, landfills that are required to operate a LFG recovery system must conduct ground-based SEM surveys three times per year in the area of the landfill where LFG is recovered to confirm that the surface methane concentrations are below 500 ppmv (Québec 2005).

### 6.1 Sources of ground-level methane emissions

This section describes the common sources of landfill emissions that SEM surveys may target.

#### Active face

The active working face of the landfill is a significant source of methane emissions, due to the presence of newer waste having a high methane generation rate and the absence of intermediate or final cover material. The active working face is typically excluded from regulatory limits for methane concentrations and from SEM surveys due to limited accessibility and health and safety considerations. Some emerging SEM approaches, such as the drone-based column laser method discussed in Section 6.3, may allow the measurement of methane concentrations at the active face.

#### Landfill cover

LFG migrates through the daily, intermediate or final landfill cover through advection and/or diffusion, resulting in diffuse methane emissions to the atmosphere. Methane emissions can vary widely as a function of the landfill cover materials and their thickness, with the highest emissions generally associated with daily cover and the lowest emissions associated with final cover. Areas of preferential LFG flow through the cover can also develop due to: erosion of the landfill cover; desiccation or waste settlement that creates cracks and fissures in cover soils; or other damage to cover materials including

geosynthetic layers. In addition to visual indicators of compromised cover materials, stressed vegetation is also an indicator of potential methane emissions.

Other potential sources of methane emissions through the landfill cover include landfill edges and side slopes, where lower compaction rates may result in less resistance to LFG migration through the waste mass, as well as cover anchor trenches and interfaces between intermediate or final cover on adjoining cells.

### **Landfill cover penetrations**

Landfill cover penetrations are objects that completely pass through the cover and may present a pathway for LFG to preferentially migrate out of the waste mass to the atmosphere. Cover penetrations include elements of the landfill gas system or leachate recovery system such as landfill gas recovery wells, leachate risers, condensate sumps and valve vaults. Fugitive methane emissions can occur at cover penetrations due to damaged seals or well boots, or damaged or loose infrastructure or connections.

### **Leachate infrastructure**

Leachate recovery systems may provide preferential pathways for LFG to collect in granular fill or perforated pipes and then discharge through the top of leachate maintenance holes.

## **6.2 Considerations for SEM planning**

This section describes factors that may affect the execution and results of SEM surveys. Applicable regulations or operating permits may provide specific requirements related to the conditions under which SEM surveys should be carried out. Advance site preparation (if needed) and a review of anticipated weather conditions should be completed prior to scheduling monitoring events.

### **General site conditions**

An SEM survey should be conducted while the LFG recovery system is operating under normal conditions and should be scheduled to avoid landfill operations that may limit access.

Before initiating an SEM survey, a desktop review of the area to be monitored should be conducted to determine the size and layout of the site, transect locations, cover penetrations, and potential areas of fugitive methane emissions based on site information and previous survey results.

The federal *Landfill Methane Regulations* require measurement of surface methane concentrations three times per year (January-May; June-August; September-December), with at least 60 days between surveys (17(1)).

Reduced frequency of surface methane monitoring is allowed as follows:

- In a portion of an open landfill that is under final cover, if there were no surface methane concentration exceedances during the previous calendar year, surface methane monitoring along transects of the landfill surface (as per 19(5(b))) may be completed once per year. All other surface methane monitoring (including at landfill cover penetrations and around the perimeter of the landfill) must be completed three times per year (17(3))
- At a closed landfill under final cover, if there were no surface methane concentration exceedances during the previous calendar year, all surface methane monitoring may be completed once per year (17(4)).

Where a zone-average surface methane concentration assessment is required as part of the survey, the entire landfill surface should be divided into individually identified zones of approximately 4,500 m<sup>2</sup> (50,000 square feet) and shown on a site plan. Recognizing the irregular shape and size of a landfill, the size of individual zones may need to be slightly larger or smaller than the recommended (or required) area.

The federal *Landfill Methane Regulations* require measurement of surface methane concentrations in the areas of the landfill where waste disposal has not taken place in the 12-month period prior to a monitoring event (17(2)).

Monitoring is not required in any portion of the landfill where a landfill cover or an active landfill gas recovery system is under construction (19(6)(a)).

### **Requirements for drone use**

Specific planning is required if a drone-based survey is to be carried out. Drone pilots must follow the rules set out in the *Canadian Aviation Regulations* (Transport Canada 2025), understand any local airspace restrictions, and consider the need for a designated visual observer. Locations for the drone set-up, pilot/observer base, and take-offs and landings should be identified prior to the survey. The pre-survey review should also identify any potential obstructions to the drone survey, including overhead wires. Planning should address the need for the regular switch-out and charging of drone batteries during the survey.

### **Weather conditions**

SEM operators may choose to schedule SEM surveys outside of periods of precipitation due to potential impacts on field equipment. In addition, SEM results may be affected by precipitation during the days preceding the survey where LFG movement may be impeded due to saturated landfill cover soils.

High winds can limit the operator's ability to accurately detect surface methane concentrations through increased dilution. Any drone to be used for SEM will also have a maximum allowable windspeed for safe operations.

The effect of changes in barometric pressure on landfill methane emissions is well documented. Rising barometric pressure tends to suppress emissions, while falling barometric pressure enhances them, a phenomenon called barometric pumping. As a result, barometric pressure conditions during a SEM survey can affect results of surface methane concentration measurements.

### **Micrometeorological instruments and measurements**

An on-site stationary or portable hand-held anemometer with a continuous recorder should be used to measure wind speed on-site. Other time-stamped meteorological data should also be collected on-site or acquired from a nearby meteorological station, including:

- atmospheric pressure
- ambient temperature
- precipitation

The federal *Landfill Methane Regulations* require that surface methane concentrations are not to be taken if:

- there is standing water on the landfill surface at the measurement location (19(7)(a))
- the average wind speed measured during a 15-minute interval using an anemometer equipped with a continuous recorder and data logger exceeds 30 kilometres per hour (19(7)(b))

The federal *Landfill Methane Regulations* require measurement of:

- the hourly rate of change of barometric pressure during the monitoring event and the 24-hour period before it (21(f)(i))
- the average wind speed measured for every 15-minute interval during the monitoring event using an anemometer equipped with a continuous recorder and data logger (21(f)(ii))

## Vegetation

Common ground- and drone-based SEM techniques require the methane detector inlet to be maintained near the landfill surface. Mowing of the landfill's vegetative cover may be required to facilitate SEM surveys. Specialized equipment may be required to mow the side slopes. Applicable regulations related to protected habitats, such the *Migratory Birds Regulations, 2022*, should also be considered when planning mowing and SEM surveys.

Under the federal *Landfill Methane Regulations*, surface methane concentrations are to be measured with the probe inlet placed no more than 5 cm above the landfill surface (19(3)), which may require mowing of tall vegetation.

## 6.3 Ground-based survey method

SEM ground-based surveys consist of walking the landfill surface following a pre-determined route and measuring methane concentrations immediately above the ground surface using a portable methane detector. This method may be used for stand-alone SEM surveys. In addition, some elements of this method may be employed as part of ground-based verification following a drone-based SEM survey (described in Section 6.4).

### Instrumentation

Typical ground-based SEM techniques employ handheld instruments based on US EPA Method 21 (US EPA 2017), incorporating FID or TDLAS detectors that use a sampling pump to continuously draw in air at a constant flow rate and measure the concentration of methane within the detector, in units of ppmv.

The federal *Landfill Methane Regulations* allow the use of a portable handheld instrument for surface methane concentrations, based on US EPA Method 21 (19(1)(a)).

An instrument meeting the following specifications is required:

- The instrument shall be capable of measuring 500 ppmv of methane with a resolution of 12.5 ppmv.

- The instrument shall be equipped with an electrically driven pump to ensure that a sample is provided to the detector at a constant flow rate. The nominal sample flow rate, as measured at the sample probe tip, shall be 0.10 to 3.0 l/min when the probe is fitted with a glass wool plug or filter that may be used to prevent plugging of the instrument.
- The instrument shall be equipped with a probe or probe extension not to exceed 6.4 mm in outside diameter, with a single end opening for admission of sample.

The following tests must be completed before the instrument is used each day:

- Calibration precision test. Make a total of three measurements by alternately using zero gas (less than 10 ppmv methane) and the specified calibration gas (500 ppmv of methane accurate to within 2 percent). Record the meter readings. Calculate the average algebraic difference between the meter readings and the known value. Divide this average difference by the known calibration value and multiply by 100 to express the resulting calibration precision as a percentage. The calibration precision shall be no more than 10 percent.
- Response time test. Introduce zero gas (less than 10 ppmv methane) into the instrument sample probe. When the meter reading has stabilized, switch quickly to the calibration gas (500 ppmv of methane). After switching, measure the time required to attain 450 ppmv (90 percent of the final stable reading of 500 ppmv). Perform this test sequence three times and calculate the average response time. The average instrument response time must be equal to or less than 30 seconds. The instrument pump, dilution probe (if any), sample probe, and probe filter that will be used during testing shall all be in place during the response time determination.

The instrument should also be regularly calibrated by introducing calibration gas (500 ppmv of methane) into the instrument sample probe and adjusting the instrument meter readout to correspond to the calibration gas value. Depending on the instrument, this calibration may be done by the user or the manufacturer.

## Field measurements

In a ground-based survey, measurements are collected by walking the surface of the landfill in a set pattern and sampling the air close to the landfill surface. Measurements at cover penetrations and in areas with visual indicators of possible methane emissions (distressed vegetation, cracks or seeps in cover) are also collected as part of the survey.

Typically, methane detectors continuously measure surface methane concentrations as transects are walked during the survey. Locations where concentrations above 200 ppmv are measured require additional measurements to confirm the maximum methane concentration within a 5 m radius. The *Landfill Methane Regulations* require that field measurements using a handheld detector be carried out as follows:

Surface methane concentrations are to be measured with the probe inlet placed no more than 5 cm above the landfill surface (19(3)).

Measurements are to be taken at the following locations:

- continuously, at intervals of no more than 2 m, along the entire perimeter of the portions of the landfill where municipal solid waste is in place (19(5)(a))

- continuously, at intervals of no more than 2 m, along a pattern that traverses the landfill, at intervals of no more than 30 m that are offset by 10 m for each successive monitoring event (19(5)(b))
- at all landfill cover penetrations (19(5)(c)). Cover penetration monitoring requires monitoring the location where the object (landfill gas recovery well, leachate riser, condensate sump, valve vault, etc.) meets the landfill surface. Monitoring of the parts of the object located above ground surface are addressed as part of equipment leak detection (Section 5)
- where indications of elevated concentrations of landfill gas are present, such as distressed vegetation and cracks or seeps in the landfill cover (19(5)(c))
- where a location of concern (concentration between 200 and 499 ppmv) was identified during the previous monitoring event (19(5)(d))

If a concentration above 200 ppmv is identified as transects are walked:

- surface methane concentrations must be measured within 5 m of the location of that measurement to identify the maximum surface methane concentration within that radius (19(3)(a))
- at the location of the maximum surface methane concentration, the probe must be maintained in a stationary position for twice the instrument response time before a measurement is recorded (19(3)(b))

Measurements need not be taken:

- in any portion of a landfill where a landfill cover or an active landfill gas recovery system is under construction (19(6)(a))
- where doing so poses a serious risk to human health or safety (19(6)(b))

Figure 4 illustrates transect spacing of 30 metres, offset by 10 metres in each successive SEM survey. The operator should deviate from the transect to collect measurements at cover penetrations, areas of stressed vegetation, cracks in the landfill cover or any other signs of elevated landfill gas concentrations.

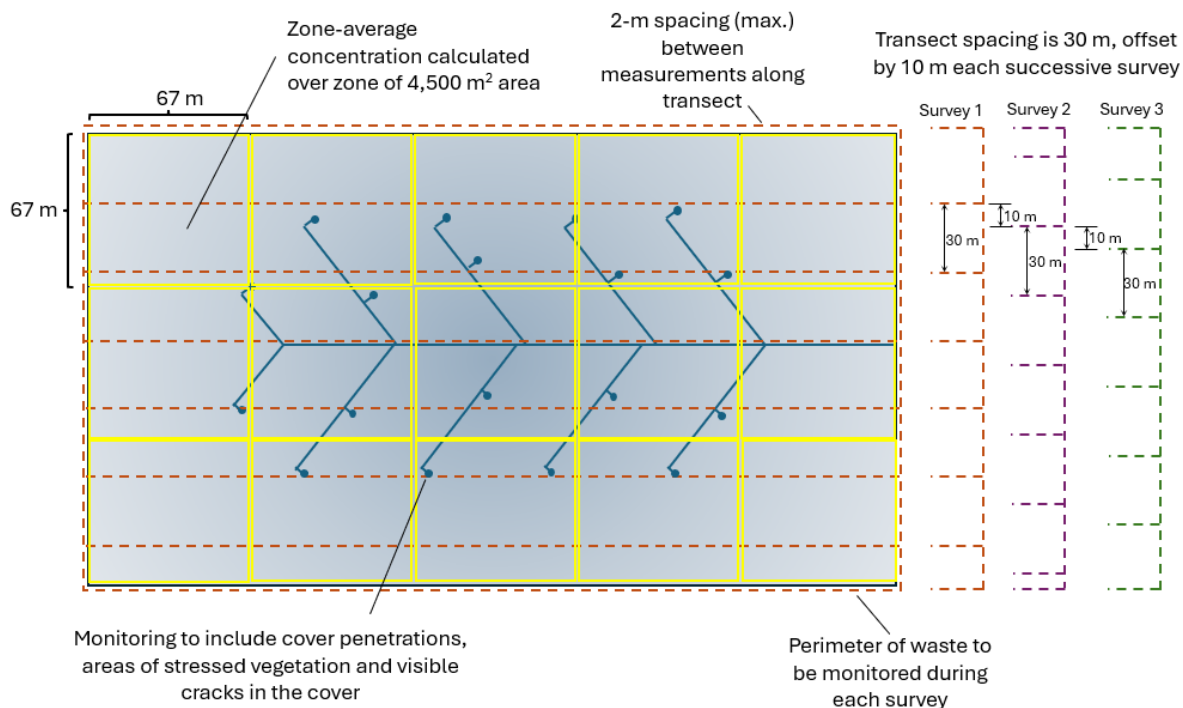


Figure 4. Example of a survey layout for surface emissions monitoring

## 6.4 Drone-based survey with sampling tube (EPA OTM-51)

The use of drones is another method for conducting SEM surveys with many similarities to SEM ground-based surveys, including collecting measurements along transects across the landfill surface. Drone-based surveys are used to replace ground-based landfill surface measurements; however, measurements of surface methane concentrations must be conducted using only the ground-based method at landfill cover penetrations and where indications of elevated concentrations of landfill gas are present.

This section describes the approach of US EPA Other Test Method (OTM) 51 (US EPA 2022), which includes a drone equipped with a methane detector payload and a sampling tube that collects air from the landfill surface. This approach enables the collection and measurement of methane concentration in air at the surface of the landfill, with methane concentrations measured in ppmv. An initial survey of the landfill surface is completed using the drone-mounted detector. At locations where elevated surface methane concentrations (“increased meter readings”) are detected, ground-based SEM is subsequently conducted to verify surface concentrations (using the instruments and measurement method described in Section 6.3).

In general, using a drone can enable the collection of screening level measurements above the surface of the landfill more quickly than a ground-based survey, and can allow for monitoring over areas of the landfill that are unsafe or impractical to access during a ground-based survey (such as very steep slopes or stormwater drainage features).

An example drone platform arrangement for conducting SEM drone surveys is shown in Figure 5.

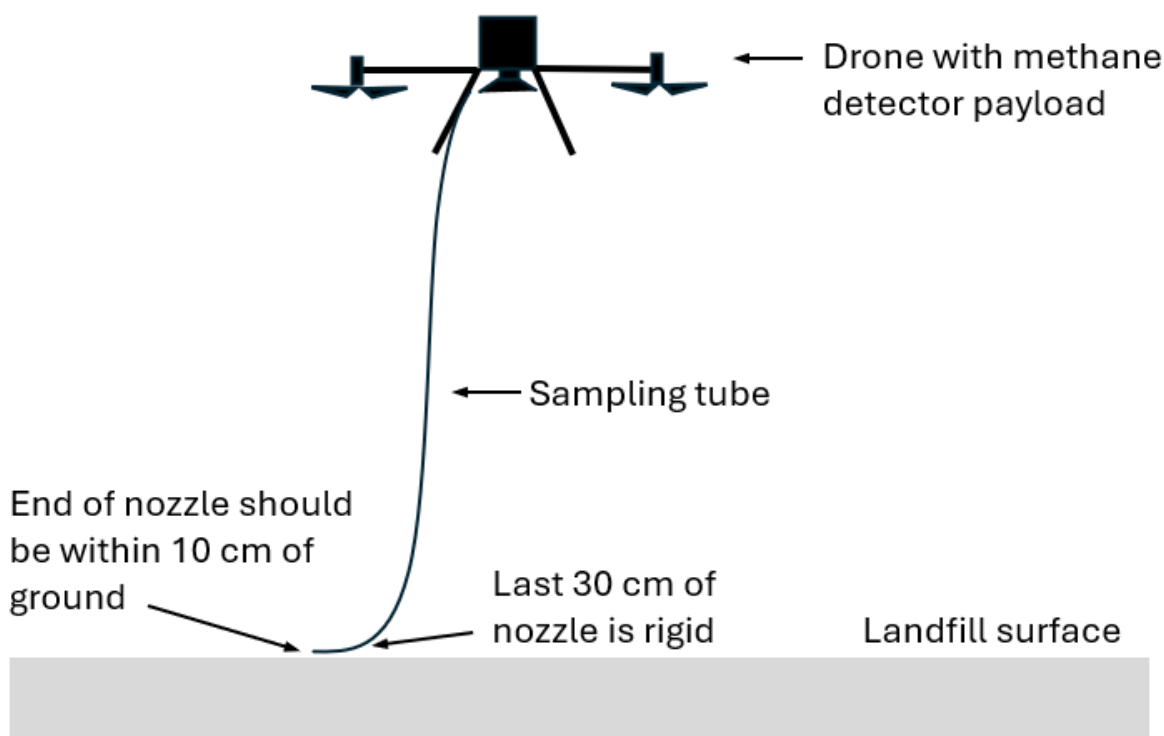


Figure 5. Components of drone-based surface emissions monitoring system

## Instrumentation

### Methane detectors

Sampling systems based on US EPA OTM 51 typically incorporate FID, NDIR or TDLAS sensors.

The federal *Landfill Methane Regulations* allow the use of a drone-mounted instrument for surface methane concentrations, based on US EPA OTM 51 (19(1)(b)).

A methane detection payload meeting the following specifications is required:

- The instrument shall be capable of measuring methane in the range from zero to at least 500 ppmv of methane with a resolution of 5 ppmv.
- The instrument shall be equipped with a pump that provides the detector a constant sample flow rate. The nominal sample flow rate, as measured at the sample probe nozzle, shall be at least 0.5 l/min when the probe is fitted with the full impedance stack of tubing, filters, and nozzle.

The methane detection instrument must be connected to a ground level sampling system (sampling tube) meeting the following specifications:

- The ground level sampling system shall be equipped with a single nozzle with inside diameter such that the air speed into the nozzle is at least 0.3 m/s.
- The ground level sampling system shall be designed to maximize the time the distal end of the nozzle is within 10 cm of ground level during flight. The nozzle shall be sufficiently weighted and the final 30 cm of the distal end of the nozzle shall be rigid.
- The ground level sampling system shall include a hose of sufficient length to drag the nozzle on the ground such that the nozzle is in fluid communication with the methane detection payload.

### **Drone platform**

The selected drone platform must be capable of safely carrying out the SEM survey. Multi-rotor drones are most commonly utilized for SEM surveys due to their maneuverability and ability to fly at very low speeds or hover over a fixed location to collect additional measurements.

The federal *Landfill Methane Regulations* require that any drone used to collect surface methane concentrations meet the following specifications, based on US EPA OTM 51 (19(1)(b)(ii)):

- The drone shall carry the methane detection payload and the ground level sampling system and use an automated, real-time measurement and control system to fly at a constant height above ground level ( $\pm 1$  meter).
- The drone shall include a data acquisition system to record both timestamped drone position (GPS coordinates with an accuracy of no worse than  $\pm 2$  meters) and methane concentration. The data shall be logged at a frequency of at least the instrument-only response time.
- The drone shall have a gimbaled camera that is remotely viewable and controllable by a remote operator in near real-time. The camera and display shall have high enough resolution for the operator to discern cover penetrations and indicators of elevated concentrations of landfill gas, including distressed vegetation, cracks or seeps in the cover, from the defined flight height above ground level. Pictures taken shall be georeferenced via metadata or similar to a GPS accuracy of no worse than  $\pm 2$  meters.
- The drone shall be in communication with an operator display that shows the methane concentration, as measured by the methane detection payload.
- If automated flight plans are used to control the path of the drone, the drone shall be controllable by the remote operator to deviate from said flight plans to inspect cover penetrations and areas where visual observations indicate potential elevated concentrations of landfill gas, such as distressed vegetation, cracks or seeps in the cover.
- The drone shall be equipped with a method to control the forward speed such that the instrument-only response time multiplied by the forward flight speed does not exceed 4 m.

### **Measurement location correction**

As the sampling tube is dragged along the landfill surface, there is a temporal and spatial offset between the collection of the sample at ground surface and its arrival at the analyzer. A series of tests must be completed prior to putting the methane detector and drone into service to calculate a correction factor applied to drone-based GPS coordinates to accurately locate surface methane measurements.

The federal *Landfill Methane Regulations* require certain tests to be completed prior to the initial use of the methane detector and drone combination, based on US EPA OTM 51 (19(1)(b)).

Several tests are required prior to putting the sampling system into service that generate information used in the determination of geographic location of measurements including:

- Instrument-only response time. Measure the instrument-only T90 response time (the time it takes for 90% of the calibration concentration to be reached) for a minimum of 5 unique tube lengths of less than 10 m. Chart results on a graph showing tube length (x-axis) and T90 response time (y-axis) and fit a linear regression to the results. If the  $r^2$  of the linear regression is greater than 0.95, the y-intercept may be recorded as the instrument-only response time.
- Nozzle offset distance. The nozzle offset distance is the horizontal distance between the drone and the distal end of the nozzle when flown at a fixed height above ground level and with a known nozzle tube length. Record the time between the drone passing a known point in space and the nozzle passing the same point in space at a known, consistent speed, hose length and height above ground level. The horizontal offset distance is the measured temporal offset of the drone to the nozzle, multiplied by the known, consistent speed. If the tube length or the planned height above ground level for the ground level sampling system changes, repeat measurements to determine the nozzle offset distance.
- Response time. The instrument pump and ground level sampling system with all filters, tubing, and nozzle lengths that will be used during testing shall all be in place during the response time determination. Introduce zero gas (less than 10 ppmv methane) into the nozzle of the ground level sampling system. When the meter reading has stabilized, switch quickly to the calibration gas (500 ppmv of methane accurate to within 2 percent). After switching, measure the time required to attain 450 ppmv (90 percent of the final stable reading of 500 ppmv). Perform this test sequence three times and record the results. Calculate the average response time. The response time shall be equal to or less than 30 seconds. If a modification to the sample pumping system or flow configuration is made that would change the response time, a new test is required before further use.
- Temporal offset between drone and methane measurement location. Derive the temporal offset from drone GPS measurement to receipt of quantified methane measurement for each combination of height above ground level and methane detection payload configuration by adding the response time for the specific flow configuration to the nozzle offset distance divided by speed. Record this time offset for input to the data acquisition system and offset the reported location of all methane measurements along the actual traversed path by this offset (i.e. if the offset is "X" seconds, the location of the measurement shall be reported as the location of the drone "X" seconds in the past).

## Calibration tests

The methane detection instrument is subject to calibration and other checks prior to each use.

The federal *Landfill Methane Regulations* require certain calibration and other checks to be completed prior to each use, based on US EPA OTM 51 (19(1)(b)).

Several calibrations and instrument tests must be completed before the instrument is used each day:

- Flow rate test. Measure the flow rate at the distal end of the collection nozzle with a flow meter readable to at least 0.1 l/min per the flow meter manufacturer's specification. Record the flow

rate; the flow rate shall be greater than 0.5 l/min. If a modification to the sample pumping system or flow configuration is made that would change the flow rate during a survey, a new test is required before further use.

- Calibration precision test. Make a total of three measurements by alternately introducing the zero gas (less than 10 ppmv of methane) and the calibration gas (500 ppmv of methane accurate to within 2 percent) where the measurement is collected via the ground level sampling system with all filters, the full tube length, and nozzle present. The introduction of the gas must be done such to not change the flow rate of the system or to pressurize the measurement cell. Record the meter readings. Calculate the average algebraic difference between the meter readings and the known value. Divide this average difference by the known calibration value and multiply by 100 to express the resulting calibration precision as a percentage. The calibration precision value shall be equal to or less than 10 percent.
- Response time test described above.

The instrument should also be regularly calibrated by introducing the calibration gas at the inlet of the ground level sampling system to include all filter, tubing, and the nozzle. Per the manufacturer's guidelines ensure the instrument readout corresponds to the calibration gas value within 10.0%. If the meter readout cannot be calibrated to the proper value and/or a malfunction of the methane detection payload is indicated, corrective actions are necessary before use.

## Field measurements

The drone-based survey follows the same transects that are used in the ground-based survey (see Figure 4). The sampling tube is dragged on or near the ground surface and collects air samples, which are drawn up to the drone-mounted methane analyzer. The *Landfill Methane Regulations* require that field measurements using a drone-mounted detector be carried out as described below:

Measurements are to be taken at the following locations:

- continuously, at intervals of no more than 2 m, along the entire perimeter of the portions of the landfill where municipal solid waste is in place (19(5)(a))
- continuously, at intervals of no more than 2 m, along a pattern that traverses the landfill, at intervals of no more than 30 m that are offset by 10 m for each successive monitoring event (19(5)(b))
- where a location of concern (concentration between 200 and 499 ppmv) was identified during the previous monitoring event (19(5)(d))

During flight, using the drone's gimbaled camera, geo-referenced pictures must be taken of features that indicate elevated concentrations of landfill gas, such as distressed vegetation and cracks or seeps in the landfill cover (19(4)(b)).

Requirements specific to the drone flight height and speed include:

- the drone must be flown at a constant height above ground level and at a speed such that the instrument-only response time multiplied by the forward flight speed does not exceed 4 m (19(4)(a))
- the time that the end of the sampling nozzle is within 10 cm of ground level should be maximized (19(1)(b))

### ***Follow-up to drone survey - Ground-based measurements***

Measurements at cover penetrations and in areas with visual indicators of possible methane emissions (distressed vegetation, cracks or seeps in cover) are not collected as part of the drone-based survey; rather, these are carried out using a handheld instrument as described in Section 6.3.

In addition, locations where concentrations above 200 ppmv are measured during the drone-based survey require verification within a 15 m radius using a handheld instrument as described in Section 6.3.

The *Landfill Methane Regulations* require that follow-up measurements be carried out using a handheld portable instrument (in adherence to the criteria and method described in Section 6.3) where a measurement above 200 ppmv was taken using the drone-mounted instrument. Ground-based follow-up is not required in any locations where drone-based readings are less than 200 ppmv.

The measurements with the handheld meter must be taken within 48 hours of the drone measurement, across the area within 15 m of the location of that measurement in a spiral or serpentine pattern at intervals of 3 m (see Figure 6).

The *Landfill Methane Regulations* also require measurements using a handheld portable instrument at the following locations (19(5)(c)):

- all landfill cover penetrations
- where indications of elevated concentrations of landfill gas are present, such as distressed vegetation and cracks or seeps in the landfill cover

For any of the above measurements, if the handheld instrument indicates a measurement above 200 ppmv:

- surface methane concentrations must be measured within 5 m of the location of that measurement to identify the maximum surface methane concentration within that radius (19(3)(a)).
- at the location of the maximum surface methane concentration, the probe must be maintained in a stationary position for twice the instrument response time before a measurement is taken (19(3)(b)).

Figure 6 illustrates the area around a drone-mounted measurement of 200 ppmv or more that requires follow-up measurement using a handheld portable instrument.

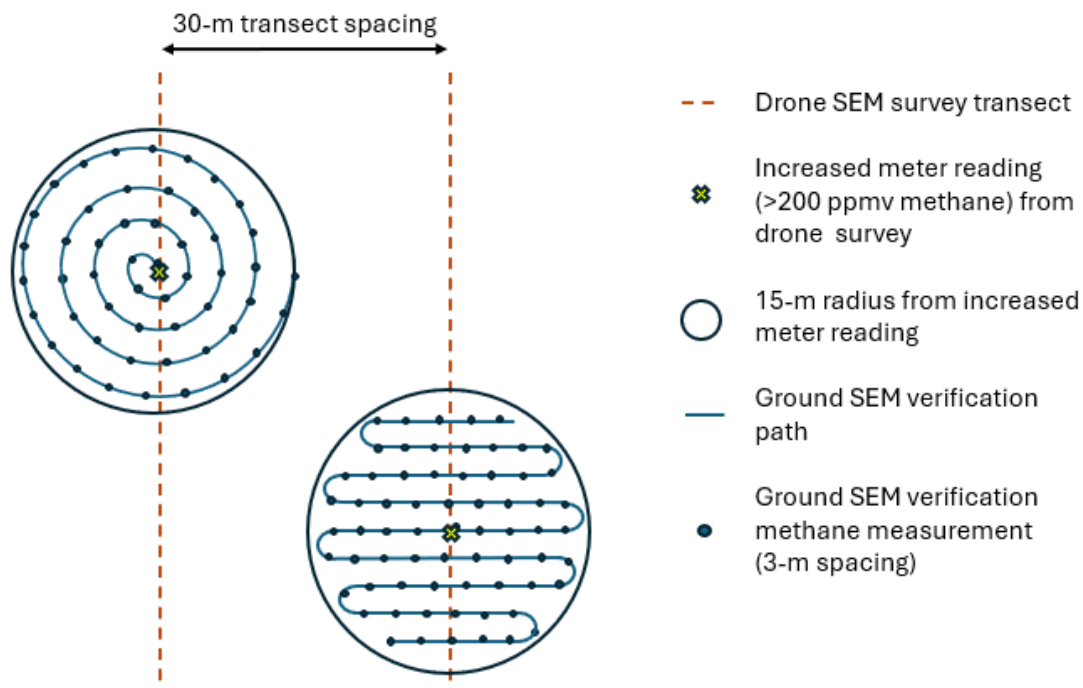


Figure 6. Ground-based verification of increased meter readings from drone survey

## 6.5 Calculation of zone-average surface methane concentration

Some regulations require the calculation of a zone-average surface methane concentration based on the individual measurements collected within a given zone (typically measuring 4,500 m<sup>2</sup> in area).

Recognizing the irregular shape and size of a landfill, the size of individual zones may need to be slightly larger or smaller than the required area.

The federal *Landfill Methane Regulations* require the calculation of the zone-average surface methane concentration for zones measuring 4,500 m<sup>2</sup>.

- Where surface methane concentrations are measured using a handheld methane detector, the zone-average concentrations are to be based on the measurements collected along the transects within the landfill (as required by 19(5)(b)). The zone average should not include measurements collected along the landfill perimeter, at cover penetrations, at areas of visible indications of potential emissions or additional measurements collected in response to increased meter readings (20(1)). Based on the maximum interval between methane measurements along the transects (2 m), there should be at least 70 to 80 data points included in the calculation of each zone-average concentration.
- Where surface methane concentrations are measured using a drone-mounted methane detector, the zone-average concentrations are to be based on all of the measurements collected using the drone (20(2)). Follow-up measurements taken using a handheld instrument should not be included in the zone-average concentrations.

## 6.6 Documentation of survey results

The results of a SEM survey typically identify locations where elevated surface methane concentrations were measured, either in the form of a map or a table listing the geographic identifiers (GPS coordinates) and the measured concentrations.

The federal *Landfill Methane Regulations* require that the following records be made for each surface methane concentration monitoring event (21):

- the date of the monitoring event and the name of the individual who conducted it
- maps showing
  - each zone and its zone identifier
  - the surface methane measurement locations (the route walked during the survey, locations of cover penetrations, locations of concern from previous monitoring event and areas with visual indication of elevated methane emissions),
  - the portions of the landfill that are under final cover and those where waste disposal has not taken place in the previous 12 months
- the dimensions (surficial area in m<sup>2</sup>) of each zone
- for any portion of the landfill that was excluded from monitoring, the reason for the exclusion and the zone identifier or a description of the portion
- the type of each monitoring instrument used, including its make and model and the results of each calibration
- the weather conditions, including the hourly rate of change of barometric pressure during the monitoring event and the 24-hour period before it, and the average wind speed measured for every 15-minute interval during the monitoring event
- the time-stamped methane concentrations, with the latitude and longitude coordinates of their locations, expressed in decimal degrees to five decimal places, and zone-average surface methane concentrations
- the location (latitude and longitude coordinates, zone identifier or well identifier) of any exceedances (methane concentration of 500 ppmv or more) or “locations of concern” (methane concentration between 200 and 499 ppmv) identified and the methane concentration at that location

Additional information that may be recorded to support follow-up mitigation activities or future surveys includes:

- Photographs of locations where elevated methane concentrations were measured

## 6.7 Drone-based survey with column laser

An alternative approach to drone-based SEM is the use of a drone-mounted, laser methane detector (typically TDLAS technology) that measures the path-integrated concentration of methane in the column of air between the drone-mounted sensor and the ground surface, with methane concentrations measured in units of ppm·m. The path-integrated concentration represents methane concentrations along the laser beam’s entire path, including any potential methane plume near the ground surface as well as the air above the plume with ambient methane levels.

The column laser method has been used by some practitioners in the United States to collect screening level measurements above the surface of the landfill, with subsequent follow-up using ground-based SEM. There is ongoing work to develop a standard method for the use of the column laser to identify elevated surface methane concentrations and quantify the associated emission rates. The standard method would include similar types of requirements as in the methods established for ground-based SEM and OTM-51, including instrument specifications, calibration, and how to collect and interpret measurements.

In order to be used as an alternative SEM method under the *Landfill Methane Regulations*, it will be necessary to describe how elevated integrated methane concentrations (ppm·m) or emission rates (kg/h) would be verified at ground surface for comparison to the concentration-based (ppmv) performance standards established in the regulations.

## 7. Quantifying landfill methane emissions

This section describes methods that may be used to quantify total site-wide methane emissions from landfills. Approaches for estimating annual methane emissions make use of modeled and measured quantities. Quantification measurements obtained from site measurements (often expressed in units of kg CH<sub>4</sub>/hour) represent the emission rate during the duration of the measurement campaign, but can be used to produce annual estimates.

Site-wide emissions estimates can be used to:

- better understand the magnitude of emissions and identify opportunities for reducing landfill methane emissions
- support more accurate input parameters to the landfill methane mass balance equation
- evaluate the effectiveness of the LFG recovery system
- support ongoing research that evaluates methane emissions from all sources, including landfills

These methods involve more complex data collection and analysis than required for SEM measurements described in the previous section. As a result, they are generally undertaken by specialized contractors or academic researchers with the required expertise and equipment. Some methods have demonstrated the ability to quantify landfill methane emissions, while others have been extensively used in oil and gas sites and are now being tested in the landfill setting. These approaches continue to be refined and validated and may offer landfill operators an opportunity to measure methane emission rates which, for some purposes, may be an improvement over the modelled estimation approach described earlier.

The following sections provide a brief overview of various approaches to methane emissions quantification.

### 7.1 Estimating methane emissions using mass balance equations

This section describes methodologies to estimate the quantity of methane that is emitted from a landfill using mass balance equations. The quantity of methane emitted is the mass of generated methane that is not recovered by the recovery system or oxidized in the landfill cover, and is therefore released to the atmosphere.

#### Methane oxidation factor

For landfills with cover systems that include soil or other organic materials (for example, compost), the methanotrophic microbial population within the soil cover will oxidize a portion of the methane as it migrates from the waste mass through the cover into the atmosphere. The methane oxidation rate in landfill cover materials is influenced by multiple factors including, but not limited to:

- type of cover materials (soil cover, biocover, etc.)
- thickness of the cover
- precipitation, temperature, barometric pressure and wind
- LFG methane concentration and
- microbial population

The industry-standard methane oxidation factor for landfills with clay/soil cover materials is 0.1 (that is, 10% of the methane that migrates through the cover system will be oxidized). The oxidation factor for landfills with a synthetic geomembrane cover system (which does not provide habitat for methanotrophic bacteria) is 0 (that is, no methane oxidation will occur). These default methane oxidation factors are consistent with the IPCC Guidelines (IPCC 2019).

A site-specific oxidation factor is appropriate for landfills with biological oxidation cover systems (biocovers). The oxidation factor must be between 0 and 1. Use of a site-specific oxidation factor should only be used if site-specific assessments of methane oxidation in the landfill cover have been completed.

### Estimating methane emissions - no landfill gas recovery system

For landfills without an operating gas recovery system, site-wide methane emissions can be estimated by subtracting the amount of methane oxidized in the cover materials from the modelled quantity of methane generated at the landfill.

*Equation 12. Landfill methane mass balance – no LFG recovery system*

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$CH_4\text{ emitted} = CH_4\text{ generated} - (CH_4\text{ generated} \times OX)$		
where		Units
$CH_4\text{ emitted}$	= Total mass of CH <sub>4</sub> emitted to the atmosphere from the landfill	tonnes CH <sub>4</sub>
$CH_4\text{ generated}$	= Total mass of CH <sub>4</sub> generated at the landfill by waste decomposition (see Section 2)	tonnes CH <sub>4</sub>
$OX$	= Methane oxidation factor	fraction

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### Estimating methane emissions - landfill gas recovery system

For landfills with an operating gas recovery system, the results from the methane generation model are combined with methane recovery information to estimate emissions. Because this approach is based on modelled or estimated values, there is a degree of uncertainty in the accuracy of results. However, these estimates can provide an indication of the order of magnitude of emissions and can serve as reference points for assessing the progress or success in meeting operational or regulatory objectives. Calculating methane emissions using upper and lower ranges of parameters (for example, methane oxidation) may be helpful in defining the potential ranges in emissions.

Site-wide methane emissions are calculated as a function of the modelled methane generation, minus the methane that is recovered and oxidized.

Equation 13. Landfill methane emissions based on modelled methane generation and methane recovery data

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$CH_4\text{ emitted} = CH_4\text{ generated} - CH_4\text{ recovered} - [(CH_4\text{ generated} - CH_4\text{ recovered}) \times OX]$		
where		Units
$CH_4\text{ emitted}$	= Total mass of CH <sub>4</sub> emitted to the atmosphere from the landfill	tonnes CH <sub>4</sub>
$CH_4\text{ generated}$	= Total mass of CH <sub>4</sub> generated at the landfill by waste decomposition (see Section 2)	tonnes CH <sub>4</sub>
$CH_4\text{ recovered}$	= Total mass of CH <sub>4</sub> recovered by LFG recovery system (see Equation 10)	tonnes CH <sub>4</sub>
$OX$	= Methane oxidation factor	fraction

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## 7.2 Measuring methane emissions

### 7.2.1 Tracer correlation method

The tracer correlation method involves the controlled release of a tracer gas from multiple locations across the landfill that are intended to represent the most significant methane-emitting sources. The tracer correlation method assumes that the tracer gas will disperse in the atmosphere in the same way as the methane emitted from the landfill. Concentrations of tracer gas and methane are measured along transects downwind of the landfill using a sensor mounted on a vehicle. Assuming the transect is at a sufficient distance downwind to promote adequate mixing and dispersion, the methane emission rate can be calculated as a function of the ratio of the integrated concentration of the emitted methane and the integrated concentration of the released tracer gas.

### 7.2.2 Airborne (aircraft/drone) active imaging

Airborne active imaging methods employ a laser that emits a beam of light, which reflects off the ground and back toward a receiver. Along its path, some light is absorbed by methane present in the air column. Changes in the reflected light are used to determine an integrated methane concentration (in ppm-m) along the path. The methane measurement equipment may be mounted on a fixed-wing or rotary-wing aircraft or on a drone.

The methane concentrations results may be used to detect emission sources (as mentioned in Section 6.7 for drone-mounted TDLAS sensors). In addition, methane concentration data and wind data may be processed to generate methane emission rate estimates for each emission source. The individual source rates may be totaled to derive an estimate of the total site emission rate.

Another approach to site emission rate quantification is to collect methane concentration measurements across vertical planes (flux planes) oriented perpendicular to the wind direction. The flux planes are typically flown both upwind (to determine the background atmospheric methane concentration) and downwind of the landfill (through the methane plume). The measurements may be taken with the laser beam oriented horizontally (between two drones positioned at the same elevation on each end of the

flux plane) or vertically (from an aircraft with the beam pointed toward the ground). Combined with wind speed and direction data, methane concentration measurements can be used to calculate a site-wide emission rate using a mass balance approach.

### **7.2.3 Airborne (aircraft/drone) in-plume sensing**

The flux plane approach described in the previous section may also be applied using sensors that measure the methane concentration (in ppmv) at the location of the sensor (as opposed to a path-integrated concentration). The sensor is mounted to a small aircraft or drone, and flux plane measurements are collected by flying multiple horizontal transects at increasing altitude levels. Alternatively, the aircraft may follow circular flight paths at increasing altitude levels to collect measurements around the entire landfill.

Combined with wind speed and direction data, methane concentration measurements can be used to calculate a site-wide emission rate using a mass balance approach.

### **7.2.4 Satellite/aircraft passive imaging**

Large landfill methane emissions can be detected and quantified based on a passive imaging approach, using imaging spectrometers mounted on aircraft and satellites. This remote sensing technique detects methane absorption of solar radiation reflected off the Earth's surface and returns an integrated methane concentration (ppm·m) along the measured column. When these concentrations are combined with wind data, an estimated emission rate can be calculated for a well-defined methane plume. Aircraft and satellite imaging spectroscopy data is available through commercial service providers. Due to the distance between the satellite and the landfill surface, satellite measurements will have a higher detection limit and coarser spatial resolution than other methods.

### **7.2.5 Mobile ground-based surveys**

Mobile ground-based surveys are conducted using a vehicle-mounted sensor to measure concentrations of methane along transects within the plume downwind of a landfill. Typically, measurements are taken along public roads adjacent to the site, far enough downwind to ensure that the methane plume has undergone sufficient atmospheric mixing.

When the measured downwind concentration measurements are combined with wind speed and direction data, a site-wide emission rate can be calculated using atmospheric inverse modelling (for example, Gaussian plume model or Lagrangian model).

### **7.2.6 Fixed continuous monitoring systems**

Continuous methane emissions monitoring can be conducted using one or more stationary instruments installed at the landfill, either at central locations or along the facility's perimeter ("fenceline" monitoring systems). These systems employ metal oxide, infrared or TDLAS sensors or optical gas imaging cameras, and may measure in-plume methane concentrations (in ppmv) or methane concentrations along a line-of-sight path (in ppm·m). Algorithms are used to continually interpret sensor measurements and assess site emissions using an inverse source dispersion model. Depending on the landfill size, many sensors may be required to achieve full site coverage.

Continuous monitoring allows for the evaluation of temporal trends, including variations in methane concentrations due to atmospheric pressure changes, precipitation events, site operations and issues

with the LFG collection system. However, these sensors have not yet been widely deployed in the landfill setting for site emission quantification.

### 7.2.7 Flux chamber studies

Flux chamber studies quantify methane emissions using sealed chambers that are temporarily installed at various locations on the landfill surface. The concentration of methane is continuously measured inside the flux chamber using a portable methane detector to assess the rate of accumulation inside the chamber. The methane flux rate at that location is calculated based on the rate of change in the concentration measurements. The total site-wide methane flux at a landfill can be calculated based on combining the results from all the flux chambers that were deployed at the site, while considering the location, cover type, surface condition for each flux chamber location, and period of deployment.

Because this method measures the flux rate at discrete sampling locations, a typical landfill may require several hundred flux chamber measurements to allow for extrapolation of a representative emission rate for the entire site. Furthermore, because the flux chambers must be installed on a flat, relatively uniform surface, these studies may be unable to measure some emission sources at a landfill, including leaks from LFG recovery wells and headers, leachate collection infrastructure, or the working face of the landfill.

## 7.3 Converting methane emissions to carbon dioxide equivalent

Methane’s warming potential as a GHG is typically estimated using the Global Warming Potential (GWP) factor, in terms of carbon dioxide equivalent (CO<sub>2</sub>-eq). The GWP was developed to express a GHG’s ability to trap heat over a specific period relative to CO<sub>2</sub>. Methane (biogenic) is estimated to have a GWP of 28 for the 100-year timescale (ECCC 2025b). To calculate the CO<sub>2</sub>-eq of a quantity of methane gas, the mass of the gas is multiplied by the specific GWP as shown on Equation 14.

*Equation 14. Converting mass of methane to carbon dioxide equivalent*

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$CH_4 CO_2\text{-eq} = CH_4 \times GWP_{100}$		
where		Units
$CH_4 CO_2\text{-eq}$	= Mass of methane in CO <sub>2</sub> -eq	tonnes CO <sub>2</sub> -eq
$CH_4$	= Mass of methane	tonnes CH <sub>4</sub>
$GWP_{100}$	= 28 (Global Warming Potential of biogenic methane for 100-year time period)	dimensionless

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## Appendix A1. ECCC Landfill Methane Modelling Tool parameters – DOC and DOC<sub>f</sub>

Material	DOC	DOC Source	DOC <sub>f</sub>	DOC <sub>f</sub> Source
Yard and garden	0.2	IPCC 2006 Guidelines (garden and park waste)	0.7	IPCC 2019 Refinement (highly decomposable waste)
Food	0.15	IPCC 2006 Guidelines	0.7	IPCC 2019 Refinement (highly decomposable waste)
Sludge	0.05	IPCC 2019 refinement (untreated sludge with 10% solids, wet weight)	0.7	IPCC 2019 refinement, ECCC estimate (assumed to be highly decomposable waste)
Paper	0.4	IPCC 2006 Guidelines	0.5	IPCC 2019 Refinement (moderately decomposable waste)
Soiled paper	0.4	IPCC 2006 Guidelines, assumed to be same as paper	0.5	IPCC 2019 Refinement (moderately decomposable waste)
Diapers and sanitary	0.24	IPCC 2006 Guidelines	0.5	IPCC 2019 Refinement (moderately decomposable waste)
Textiles	0.24	IPCC 2006 Guidelines (60% assumed to be natural fibre)	0.5	IPCC 2019 Refinement (moderately decomposable waste)
Pet waste	0.24	ECCC Estimate	0.5	IPCC 2019 Refinement, ECCC estimate (assumed to be moderately decomposable waste)
Other – Residential	0.10	ECCC Estimate	0.5	IPCC 2006 guidelines (bulk waste, moderately decomposable waste)
Other – ICI	0.05	ECCC Estimate	0.5	IPCC 2006 guidelines (bulk waste, moderately decomposable waste)
Other - Unknown	0.05	ECCC Estimate	0.5	IPCC 2006 guidelines (bulk waste, moderately decomposable waste)
Wood	0.43	IPCC 2006 Guidelines	0.1	IPCC 2019 Refinement (less decomposable waste)
Rubber and leather	0.39	IPCC 2006 Guidelines	0.1	ECCC estimate (assumed to be less decomposable waste)
Soil	0.03	ECCC estimate (estimated 3% carbon)	0.1	IPCC 2019 refinement, assumed to be less decomposable waste

## Appendix A2. ECCC Landfill Methane Modelling Tool parameters - decay rate, k (average annual precipitation-based)

	Material	Average annual precipitation-based decay rate (yr <sup>-1</sup> )					Source
		<250mm	250 to 500mm	>500 to 1000mm	>1000 to 2000mm	>2000mm	
Rapidly decaying	Food	0.03	0.05	0.09	0.185	0.185	BC LFG Generation Estimation Tool, 2009; IPCC 2006 Guidelines, Food waste, Boreal/Temperate (Wet)
	Pet waste	0.03	0.05	0.09	0.185	0.185	BC LFG Generation Estimation Tool, 2009 (Rapidly decaying waste); IPCC 2006 Guidelines, Boreal/Temperate (Wet)
	Sludge	0.03	0.05	0.09	0.185	0.185	BC LFG Generation Estimation Tool, 2009; IPCC 2006 Guidelines, Sewage sludge, Boreal/Temperate (Wet)
Moderately decaying	Yard and garden	0.03	0.05	0.09	0.11	0.12	BC LFG Generation Estimation Tool, 2009
	Diapers and sanitary	0.03	0.05	0.09	0.11	0.12	BC LFG Generation Estimation Tool, 2009 (assumed to be moderately decaying)
	Other – Residential	0.03	0.05	0.09	0.11	0.12	BC LFG Generation Estimation Tool, 2009 (assumed to be moderately decaying)
	Other – ICI	0.03	0.05	0.09	0.11	0.12	BC LFG Generation Estimation Tool, 2009 (assumed to be moderately decaying)
	Other - Unknown	0.03	0.05	0.09	0.11	0.12	BC LFG Generation Estimation Tool, 2009 (assumed to be moderately decaying)
	Soiled paper	0.03	0.05	0.09	0.11	0.12	BC LFG Generation Estimation Tool, 2009 (assumed to be moderately decaying)
Slowly decaying	Paper	0.01	0.02	0.04	0.06	0.07	BC LFG Generation Estimation Tool, 2009
	Textiles	0.01	0.02	0.04	0.06	0.07	BC LFG Generation Estimation Tool, 2009
Very slowly decaying	Wood	0.01	0.01	0.02	0.02	0.03	BC LFG Generation Estimation Tool, 2009 (assumed to be very slowly decaying)
	Rubber and leather	0.01	0.01	0.02	0.02	0.03	BC LFG Generation Estimation Tool, 2009 (assumed to be very slowly decaying)
	Soil	0.01	0.01	0.02	0.02	0.03	BC LFG Generation Estimation Tool, 2009

## Appendix A3. ECCC Landfill Methane Modelling Tool parameters - decay rate, k (climate zone-based)

	Material	Climate zone-based decay rate (yr <sup>-1</sup> )		
		Dry	Wet	Source
Rapidly decaying	Food	0.06	0.185	IPCC 2006 Guidelines, Food waste, Boreal/Temperate (Wet/Dry)
	Pet waste	0.06	0.185	IPCC 2006 Guidelines, Boreal/Temperate (Wet/Dry), assumed to be rapidly degrading waste, same as sewage sludge
	Sludge	0.06	0.185	IPCC 2006 Guidelines, Sewage sludge, Boreal/Temperate (Wet/Dry)
Moderately decaying	Yard and garden	0.05	0.1	IPCC 2006 Guidelines, Moderately degrading waste (Garden and park waste), Boreal/Temperate (Wet/Dry)
	Diapers and sanitary	0.05	0.1	IPCC 2019 Refinement, Excel model workbook
	Other – Residential	0.05	0.09	IPCC 2019 refinement (Boreal/Temperate) (assumed to be similar to bulk waste/moderately degrading waste)
	Other – ICI	0.05	0.09	IPCC 2019 refinement (Boreal/Temperate) (assumed to be similar to bulk waste/moderately degrading waste)
	Other - Unknown	0.05	0.09	IPCC 2019 refinement (Boreal/Temperate) (assumed to be similar to bulk waste/moderately degrading waste)
Slowly decaying	Soiled paper	0.05	0.1	IPCC 2006 Guidelines, Moderately degrading waste (Other, non-food, organic putrescible), Boreal/Temperate
	Paper	0.04	0.06	IPCC 2006 Guidelines, Paper/Textiles, Boreal/Temperate (Wet/Dry)
Very slowly decaying	Textiles	0.04	0.06	IPCC 2006 Guidelines, Paper/Textiles, Boreal/Temperate (Wet/Dry)
	Wood	0.02	0.03	IPCC 2006 Guidelines, Wood/Straw, Boreal/Temperate (Wet/Dry)
Very slowly decaying	Rubber and leather	0.02	0.03	Assumed to be very slowly decaying waste
	Soil	0.02	0.03	Assumed to be very slowly decaying waste

## Appendix A4. Waste category descriptions

Waste category		Description
Decomposable waste	Food	Edible and inedible food, including leftovers, spoiled food, peels, and kitchen scraps
	Paper	Paper-based materials such as newspapers, office paper, magazines, and cardboard
	Soiled paper	Paper products contaminated by food, grease, or other substances, such as napkins and food-soiled containers
	Wood	Treated and untreated wood, including lumber scraps and pallets
	Yard and garden	Organic material from outdoor maintenance, including grass clippings, leaves, branches, and plant debris
	Diapers and sanitary	Disposable hygiene products, including diapers, sanitary pads, tampons, and incontinence items
	Pet waste	Animal excrement and associated materials such as cat litter and disposal bags
	Rubber and leather	Mixed materials made from rubber and leather (e.g. belts, upholstery, footwear), excluding pure rubber materials such as tires
	Textiles	Clothing and fabric materials made from natural or synthetic fibers
	Other - Residential, Other - ICI	Includes miscellaneous or non-classifiable items (bulky waste) (sector-specific waste)
	Other - Unknown	Includes miscellaneous or non-classifiable items (bulky waste) (bulk waste)
Inert waste	Plastics	Plastic materials including containers, packaging, and single-use products
	Metals	Metal materials including cans, wires, tools, and structural components
	Glass	Glass materials including bottles, jars, broken glassware, and windowpanes
	Household hazardous waste	Corrosive, explosive, poisonous, or flammable items including paints, motor oil, propane tanks, household cleaners and detergents, pharmaceuticals, and fluorescent tubes and energy efficient bulbs
	Inert construction debris	Materials from construction and renovation activities, including drywall, bricks, tiles, concrete, asphalt and insulation (not including wood).
	Electronics	Electronic items including household appliances, computers, televisions, radios, cell phones and batteries
	Ash	Ash residue from wood or coal fires
	Rubber	Rubber materials (e.g. tires)
	Other – C&D	Includes miscellaneous or non-classifiable items (bulky waste) (sector-specific waste)