Appendix A

Methods for Estimating, Measuring, and Monitoring Landfill Methane Emissions

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1 INTRODUCTION

SCS Engineers (SCS), under the direction of Environment and Climate Change Canada (ECCC), has conducted a review of methods for estimation, measurement, and monitoring (EMM) of methane emissions from landfills. Some Canadian provinces (e.g. British Columbia, Ontario, and Quebec) have landfill methane EMM requirements, but those requirements are not nationally standardized.

The objective of the work performed by SCS is to summarize existing approaches and methods available for landfill methane EMM which are in use throughout the world and assess how they might be used in Canada.

The landfill methane EMM practices summarized in SCS Attachment 1 were identified by SCS as applicable for this study. This report will review those methods, describe why certain methods should not be further considered, and identify a short list of reasonable methods for landfill methane EMM that could be further considered for implementation in Canada.

LANDFILL METHANE EMISSION ESTIMATION

Landfill methane emission estimation is the determination of landfill methane emissions without direct measurement of those measurements. Landfill methane estimation methods should be discussed separately for landfills without active[1] landfill gas (LFG) collection and control systems (GCCS) and for sites with an active GCCS. This separate discussion is needed because landfills without a GCCS typically have no way to measure LFG flow or emission, but sites with an active GCCS can measure the flow and methane content of collected LFG. This measurement provides a reference that can be used to determine methane generation and emission.

Landfills without Active GCCS

Landfills without an active GCCS typically have no way to monitor methane generation or emission without a sampling event. Options for sampling programs are discussed in the methane measurement and monitoring sections.

The only way to estimate methane emissions from a landfill without an active GCCS, and therefore no means of measurement of methane collection or emission, is to model methane generation or emission. SCS identified the following modeling methods for landfills without a GCCS:

- First order decay (FOD) modeling (Method A-1)
- Non-FOD modeling (Method A-2)

[1] "Active" means a GCCS with a blower that creates a pressure differential to draw LFG out of the waste area. It does not mean a system where gas movement is driven by pressure gradients created by only the generation of LFG (i.e. a passive GCCS).

FOD Models (Method A-1)

FOD modeling is widely accepted as the preferred method for estimating methane generation. It is used to estimate greenhouse gas (GHG) emissions from landfills by the United States Environmental Protection Agency (EPA) as part of the Greenhouse Gas Reporting Program (GHGRP), the California Air Resources Board (CARB) as part of the Landfill Methane Control Measure (LMCM), and the Intergovernmental Panel on Climate Change (IPCC). The FOD modeling approach to determining methane generation in landfills dates back at least to the development of the Scholl Canyon Gas Generation Model, the Sheldon Arleta Model, and the Palos Verdes Model, all developed in the mid1970s.

FOD models have the advantage of easy-to-understand inputs (e.g. waste tonnage, decay rate, methane generation potential) and the ability of users to customize the sophistication of the calculation method. This customization was evident from the beginning of the use of the FOD models; the Scholl Canyon Model used a single decomposition stage and rate, while the Sheldon Arleta Model and the Palos Verdes Model used multiple decomposition stages and rates. FOD models are a viable method for estimating methane emissions from landfills.

The two most relevant implementations of the FOD model are the EPA's LFG Emission Model (LandGEM), and the IPCC Solid Waste Disposal model. California utilizes a state-specific implementation of the IPCC model. The FOD model used by British Columbia is a FOD model derived from the Scholl Canyon Model and similar to LandGEM but with more fine tuning options available for waste type and decay rate. LandGEM is developed from the Scholl Canyon Model and is used routinely in the United States for regulatory compliance and permitting. The IPCC is a more generalized FOD model intended to be applicable anywhere in the world. This is the model used in Canada for the National Inventory Report estimates of methane emissions from municipal solid waste landfills.

Parameters critical to the function of the FOD model are the decay rate (k) and the potential of the waste to generate methane (L_0 or a combination of other factors that are functionally equivalent to L_0). This evaluation will use "L_0" when discussing the parameter that represents the potential to generate methane for simplicity and brevity. Simple implementations of the FOD model based both the k and L_0 value on municipal solid waste (MSW), while more complex implementations (e.g. the IPCC model) use a separate k and L_0 value for each waste type. Table 1 shows a summary of k and L_0 or equivalent values from models and literature.

Table 1. Critical FOD Model Parameters

Source	Waste Type	k ($year^{-1}$)	L_0 (m^3 LFG/Mg waste)
LandGEM	MSW	0.02-0.04	100
GHGRP	MSW	0.02-0.57	101

	C&D	0.02-0.04	41
	Inert	0	0
	Food	0.06-.185	76
	Garden	0.05-.1	101
	Paper	0.04-0.06	203
	Wood and straw	0.02-0.03	218
	Textiles	0.04-0.06	122
	Diapers	0.05-0.1	122
	Sludge	0.06-0.185	0
	Industrial waste	0.08-0.1	76
California LMCM	MSW	0.02-0.057	68-110
	Greenwaste	0.02-0.057	63
	Sludge	0.02-0.057	25
IPCC	Food	0.1–0.2	76
	Garden	0.06–0.1	101
	Paper	0.05–0.07	203
	Wood and straw	0.02–0.04	218
	Textiles	0.05–0.07	122
	Nappies	0.06–0.1	122
	Sludge	0.1–0.2	25
	Industrial waste	0.08-0.1	76

After methane generation is determined with the FOD model, methane emissions can be estimated by deducting any methane oxidation in landfill cover or methane destruction in passive destruction systems from the methane generation and assuming that the remainder is emitted to the atmosphere. The EPA has used a methane oxidation rate of 10 percent in landfill cover historically. Solid Waste Industry for Climate Solutions (SWICS), an industry group that includes SCS, worked with academics to develop better estimations of methane oxidation in landfill cover, proposed the use of oxidation rates that depend on the flux rate of methane through the landfill cover (SWICS 2009). This approach was later adopted by the EPA as part of the GHGRP. SWICS alternatively proposed basing the oxidation rate on the landfill cover material, but this approach was not adopted by the EPA.

FOD models are known to be inaccurate for the estimation of landfill methane generation for individual sites, but a review of data collected by SCS as part of the EPA's GHG reporting program suggests that the data may be more accurate when aggregated nationally, such as for a national inventory. Individual sites have demonstrated methane recovery of more than twice what the FOD modeled generation predicted, and SCS believes that the model can similarly over predict methane generation by a factor of more than two for individual sites. In its “Compilation of Air Pollutant Emission Factors” document (AP-42), the EPA estimates that the predicted methane emissions varied from 38 to 492 percent of actual emissions. The inaccuracy can be reduced by robust characterization of the waste stream at each landfill, but the required level of characterization is more detailed than standard industry practice in the United States or Canada. Both the EPA and California have used three waste types in their intermediate complexity categorizations, but those waste types differ. The EPA categorizes waste as MSW, Construction and Demolition (C&D), and inerts, while California uses MSW, greenwaste, and sludge. The IPCC model categorizes waste into eight categories. The intermediate complexity approach of using small number of categories (3-5) with k and L_0 factors developed using national waste characterization studies provides the most refinement without significantly increasing the burden on landfills to categorize waste. The waste characterization studies should be conducted to categorize waste type consistently with IPCC categories or other existing sources for k and L_0 values.

Limited improvements in the waste characterization could be done on the regional or provincial level. California’s implementation of the IPCC model as part of their LMCM regulation, which was part of the state’s Assembly Bill 32 (AB32) climate change program, is one such example (CARB 2011). California’s historical waste characterization data is sufficiently robust that the IPCC model used in the LMC regulation uses a methane generation potential that varies by year based on statewide waste characterization studies. A generalized FOD model (i.e. IPCC or EPA default parameters) would be a Tier II IPCC method, and a FOD model with national developed key parameters or measurement derived country-specific parameters would be considered a Tier III method. A Tier III method is a “validated higher quality” method. Key parameters to be considered a Tier III method include the decay rate and the methane generation potential. Such an approach is used for Canada’s National Inventory Report, where temporal differences in waste characterization are used to calculate the fraction of degradable organic carbon that decomposes (DOC_f) (one of the factors that goes into calculating the L_0 parameter) values for four time periods for each province and territory. Provincial and territorial specific k values are calculated.

The use of the FOD model for calculating methane generation is appropriate for landfills of all sizes. The cost of modeling is independent of the size of the landfill, so the relative cost will be greater for small landfills. Costs for using FOD models will be in the high hundreds of dollars to low thousands of dollars. SCS does not expect logistical limitations associated with this method; however, understanding the inherent uncertainty with the FOD models is critical.

Non-FOD Models without Gas Collection (Method A-2)

The use of non-FOD modeling to determine landfill methane emissions is relatively uncommon. The only non-FOD model SCS could find that is still in development is the California Landfill Methane Inventory Model (CALMIM), which was developed for use in California, but its development is supported by the EPA. CALMIM is a one-dimensional transport and oxidation model for landfill methane. Non-FOD models are a viable method for estimating methane emissions from landfills but typically require different inputs such as the amount of organic matter in cover materials and detailed climate information. CALMIM calculates methane emissions based on modeled methane transport in the landfill cover materials and methane oxidation in the landfill cover.

CALMIM was developed using California landfills, but has been vetted internationally as a potential reporting method for the IPCC (Bogner et. al. 2011). The IPCC concluded that CALMIM is a Tier III methodology for determining landfill methane emissions.

The use of a non-FOD model for calculating methane generation is appropriate for landfills of all sizes. The cost of modeling is independent of the size of the landfill, so the relative cost will be greater for small landfills. Non-FOD models require data that is outside of what landfills typically record and maintain, and they are more complicated to use, so costs for using non-FOD models to estimate methane emissions tend to be higher than costs for using FOD models. Costs for using nonFOD models will be in the low thousands of dollars to low tens of thousands of dollars, depending on the amount of additional data collection. SCS does not expect logistical limitations associated with this method; however, the additional data collection needs must be considered.

Landfills with Active GCCS

Landfills with active LFG collection can measure the flow and methane concentration in the collected LFG. This additional measurement data results in the following options for methane emission estimation methods:

- FOD modeling with measured LFG collection (Method A-3)
- Non-FOD models (Method A-4)
- Measured LFG collection with estimated collection efficiency (Method A-5)

FOD Modeling with Measured LFG Collection (Method A-3)

In this method, methane generation is modeled with a FOD model and measured methane recovery is deducted from the methane passing through the landfill cover as fugitive emissions. Emissions from the recovered methane are measured and calculated as per a stationary combustion device or other process (e.g. carbon adsorption system [CAS], compressed natural gas [CNG] production). The general form of the emission calculation is shown in Equation 1.

Equation 1: $EEEEEEEEEEEEEEEEEE = (GGGGEE - RRGGRREEvvGGvvvv) xx (1 - OOxxEEOOOOOOEEEEEE)$

Where “Emissions” is the mass of methane emitted, “Gen” is the mass of methane generated as calculated by the FOD model, “Recovery” is the measured methane recovered by the active GCCS, and “Oxidation” is the fraction of methane oxidized in the landfill cover.

FOD modeling with methane recovery is a viable method for estimating methane emissions from landfills. The EPA’s GHGRP uses this method for calculating GHG emissions. This method is also included in the IPCC Solid Waste Disposal inventory method.

Because this method for methane emission estimation relies on FOD modeling as the basis for estimating methane emissions, it inherits the accuracy, uncertainty and limitations of the FOD modeling. The inaccuracy of FOD modeling can become apparent when the recovered methane exceeds modeled methane generation. The model over predicting methane generation is not as apparent because there is not an obvious discrepancy (i.e. the recovered methane exceeding the modeled methane generation), but the model is known to over predict methane generation for individual sites as well.

The costs for this method are higher than FOD modeling alone because of the additional costs associated with monitoring and processing the methane recovery data. Costs for this method will be in the low to mid thousands. Costs will have some scaling associated with the number of methane measurement locations/methane destruction devices. SCS does not expect logistical limitations associated with this method for facilities that are already operating an active GCCS.

Non-FOD Models with LFG Collection (Method A-4)

Non-FOD models were previously discussed above. The presence of an active GCCS may limit some of the non-FOD models use for methane emission estimates, but CALMIM can be used for sites with a GCCS. CALMIM allows for users to input the area of the landfill with an active GCCS, and it calculates the methane emissions based on the area with coverage. Unlike the Methods A-3 and A-5, CALMIM does not require information about the amount of waste placed in each year or the amount of methane collected by the GCCS.

Measured Recovery with Estimated Recovery Efficiency (Method A-5)

In this method, methane recovery is measured, the methane recovery fraction (collection efficiency) is estimated, and the methane generation is calculated based on those factors. The difference between the calculated methane generation and recovered methane is assumed to pass through the landfill surface, undergo oxidation, and be emitted to the atmosphere. Emissions from the recovered methane are measured and calculated as per a stationary combustion device or other process. The general form of the emission calculation is shown in Equation 2.

RRRRRRRRRRRRRRRR

Equation 2: $EEEEEEEEEEEEEEEEE = (\underline{\qquad\qquad}$
$-RRGGRREEvvGGvvvv)xx(1-OOxxEEOOOOOOEEEEEE)$

CCRRCCCCRRRRCCCCRRCC RReeee

Where “Emissions” is the mass of methane emitted, “Recovery” is the measured methane recovered by the active GCCS, “Collection eff” is the estimated collection efficiency of the GCCS, and “Oxidation” is the fraction of methane oxidized in the landfill cover.

Measuring methane recovery and estimating collection efficiency is a viable way of estimating methane emissions from landfills. This methane estimation method was developed by Solid Waste Industry for Climate Solutions (SWICS), an industry group that includes SCS, who collaborated with academics to develop the method and estimates for collection efficiencies (SWICS 2009). A modified version of the SWICS method is also used in the EPA GHGRP.

Collection efficiency is difficult to measure directly, and the uncertainty/accuracy of this method is associated with the uncertainty of that factor. Historically, the EPA estimated that landfills with gas recovery collected 75 percent of the generated methane. The GHGRP uses the surface area by cover type to estimate collection efficiency. SWICS and the EPA used landfill cover type (e.g. daily, intermediate, and final) to determine site specific collection efficiency. Each cover type has an associated collection efficiency, and the overall facility collection efficiency is the area weighted average of those collection efficiencies. SWICS also recommends the consideration of monitoring results, engineering review of the comprehensiveness of the GCCS, and other site specific data when evaluating collection efficiency for each cover type or area; however, this was not incorporated by the EPA into the GHGRP.

Site specific without using collection efficiency estimation requires measurement of methane emissions, which is discussed in in the next section.

The use of a fixed or default collection efficiency should be avoided because it could provide a perverse incentive to reduce methane recovery and destruction. In this case, reduced methane recovery would result in lower calculated methane generation and lower calculated emissions, but actual methane emissions would be higher because actual methane generation would remain the same (see Equation 1).

Costs for this method are similar to costs for the use of a FOD model with measured methane collection. Costs for this method will be in the low to mid thousands. Costs will have some scaling associated with the number of methane measurement locations/methane destruction devices. SCS does not expect logistical limitations associated with this method for facilities that are already operating an active GCCS.

State of the Emission Estimation Practice in Canada

Even in the absence of a regulatory driver to estimate methane emissions, landfills may want to model methane generation to as part of a program to control offsite gas migration, reduce odor emissions, or for energy recovery. Based on the experience of SCS and the other consultants it discussed the issue with, the most common approach to modeling methane generation is the use of LandGEM, sometimes with the use of province-specific decay rate and methane generation potential values. More sophisticated FOD models, such as the British Columbia Model or the IPCC Model, are sometimes used, but this practice is less common.

The province of British Columbia's Landfill Gas Management Regulation requires landfills that have 100,000 megagrams or more of MSW in place or that receive 10,000 or more megagrams of MSW in any calendar year after 2008 to prepare an LFG Generation Assessment. Existing guidance - the Landfill Gas Generation Assessment Procedure Guidelines - specifies use of the Scholl Canyon model in conducting this assessment and provides direction on default values for several parameters. A Landfill Gas Generation Estimate Tool (Microsoft Excel spreadsheet) is available to landfill owners to assist in this analysis.

Recommended Approach for Landfills without Active GCCS

For landfills without a GCCS, SCS recommends the use of a FOD model derived from the IPCC model with k and L_0 parameters tuned for the region, similar to the California implementation of the IPCC model or British Columbia's implementation of the Scholl Canyon Model (Method A-1). Regional k and L_0 values could be developed with waste characterization data that categorizes the waste stream into categories for which values of k and L_0 have been developed (e.g. IPCC categories). Sitespecific k values can be determined by pump test methods, such as EPA New Source Performance Standards (NSPS) Tier 3 testing. Inputs used in the model should be more descriptive than in the British Columbia Model. That is, waste type inputs should be descriptive (e.g. municipal solid waste, greenwaste, food waste, inert) rather than the inputs used in the British Columbia Model (e.g. relatively inert, moderately decomposable, decomposable) so it is easier to directly utilize data gathered through waste characterization studies.

The FOD model is preferred over non-FOD models because it predicts LFG generation, which is useful for purposes other than estimation of landfill methane emissions and for consistency with industry and international practice. Also, these tend to be less costly than other options and can be finetuned over time with minimal additional effort. However, research into non-FOD models is ongoing and they may become more widely accepted.

Recommended Approach for Landfills with an Active GCCS

For landfills with a GCCS, SCS recommends the use of measured methane recovery with estimated collection efficiency (Method A-2). The method should require a site specific estimation of collection efficiency, especially if methane emission estimates are tied to a financial consequence (e.g. carbon tax, cap and trade program). SWICS and the EPA both based the estimation of collection efficiency on the cover types used (e.g. daily, intermediate, and final) at the landfill and the extent of the GCCS.

Allowing for more engineering judgement for individual sites would be appropriate if the methane emission estimate is used for informational or inventory purposes (e.g. SWICS version). A more rigid system would be appropriate if the methane emission estimate is tied to a financial consideration to avoid gaming of that financial system, and to promote consistency among landfills in a regulatory program (e.g. EPA version).

LANDFILL METHANE MEASUREMENT

Landfill methane measurement is the direct measurement of methane emissions from landfills. SCS identified four categories of methane measurements in the previous annotated list. All of these measurement methods are substantially more expensive than methane emission estimation methods due to the large amount of fieldwork, equipment, and analysis used in the methods. The categories previously identified are:

- Flux chamber testing (Method B-1)
- Plume measurement(Method B-2)

- Micrometeorology measurement (Method B-3)
- Dispersion modeling (Method B-4)

Flux Chamber Testing (Method B-1)

Flux chamber testing is the sampling of methane flux (mass emissions per area) at the landfill surface using flux chambers. Flux chambers are small (typically around one [1] square meter) half open chambers (typically a dome) that are placed on the surface being sampled. Sample locations are very small compared to the area of even a small landfill, so flux chamber testing must include a method of scaling the sampling results for the complete site.

The EPA has developed a method that includes the determination of the number of required samples and sample locations (Radian 1986), but the number of samples required for even a small landfill is impractical. A ten (10) acre site (4 hectares) would require 37 sample locations, several days of fieldwork, tens of thousands in analytical costs, and days of labor to prepare the emission report. Large sites would require many more samples with proportionately larger costs.

Alternative sampling strategies have been proposed and developed, including a strategy that combines surface emission monitoring (SEM) with flux chamber sample location siting. The method was developed by Thomas Card of Environmental Management Consulting.

Neither the method developed by the EPA or alternative methods are required for regulatory compliance. It is typically used to demonstrate emissions from a facility for academic or other nonregulatory reasons.

The number of samples required by the EPA in its flux chamber sampling guidance was developed to achieve a 95 percent confidence that the sitewide flux rate is within 20 percent of the actual flux rate. Flux chambers can be used at most landfills. Because sampling requires extended access to surface areas of the landfill, some landfills may have large areas that cannot be sampled due to safety concerns. Flux chamber sampling should not occur shortly after precipitation or while ground is covered with snow, so the period during which many landfills can be sampled will be limited.

Costs for flux sampling events will be in the range of mid to high tens of thousands of dollars for flux testing with SEM screening. Cost for a single flux sampling event using the EPA statistical method will be in the low hundreds of thousands of dollars to mid hundreds of thousands of dollars.

Plume Measurement (Method B-2)

Optical plume measurement uses a ground based optical sensor to measure the methane plume coming from a landfill. Those plume measurements are then used to calculate the methane emission rate from a landfill. There is currently no standardized optical sensor method. The EPA has published Other Test Method 10 (OTM 10), but it has generally fallen out of use and is not regarded as practical or accurate enough for regular use. The EPA is not currently recommending this method on sites they regulate, but they have recently required monitoring using eddy covariance for specially regulated sites.

Due to the large cost (i.e. high tens of thousands of dollars to mid hundreds of thousands of dollars), specialized knowledge required to operate, unknown accuracy, further development of other methods (e.g. eddy covariance), poor consistency and repeatability of results in studies done to date, and restrictive operating conditions, ground based optical sensor methods have fallen out of favor, and SCS does not recommend further consideration of plume measurement methods.

Micrometeorology Measurement (Method B-3)

Other optical sensor methods use methane concentration measurements collected along fewer paths rather than measuring many paths to determine the size of a plume. This review will primarily discuss eddy covariance, the most common micrometeorology method.. Most of these findings could also be applied to other micrometeorology methods, including eddy accumulation and Bowen. These methods are similar to eddy covariance, and rely on similar sensors and similar strengths and limitations. Eddy covariance is discussed in this paper because it is well understood and commercial packages for monitoring are available.

In these methods, the concentration of methane between fixed points is used to calculate the methane flux from a source. Concentration of atmospheric methane is measured using an infrared laser. Micrometeorology measurements are generally superior to plume measurements because some equipment packages can remain in place and provide regular monitoring over extended periods. There are numerous competing software packages that can be used to calculate flux using eddy covariance.

Eddy covariance is well demonstrated in other applications, such as monitoring benthic oxygen flux in the ocean, monitoring atmospheric carbon dioxide flux, and micrometeorology. The principles of eddy covariance were developed in the 1950s, but hardware and computational requirements limited the application. Recent developments and improvements in the cost and capability ultrasonic anemometers, gas sensors, and computational power have led to its wider use over the last decade.

No regulations require the use of eddy covariance, but SCS is aware of one facility that is required to use eddy covariance measurement of methane emissions as part of a research permit. Similarly, there is no standard eddy covariance method from a regulatory agency. Eddy covariance is primarily used in academic research.

Eddy covariance has substantial data recording and management requirements, which benefit from more robust and less expensive storage and wider cellular coverage for data transmission. Eddy covariance is probably the most accurate of the measurement methods reviewed by SCS under most circumstances. Technical limitations of eddy covariance include power and data transfer requirements. The method is also limited during heavy precipitation, and dew, snow, and frost can interfere with measurements. For these reasons, eddy covariance is best suited to arid sites with access to power and cellular data coverage, though it can be used in wetter climates. The use of battery power and manual data collection is possible at sites without power or data coverage. Some eddy covariance packages require frequent (up to daily) calibration. The knowledge and skillset required to design and implement eddy covariance monitoring is not common among landfill specialists, but many large environmental and engineering consulting companies will have monitoring groups that would have the required knowledge and skills. Costs for this measurement method are in the low to mid hundreds of thousands of dollars per site.

Air Dispersion Modeling (Method B-4)

Air dispersion emission calculation methodologies use field measurement of methane concentration data and contemporaneous meteorology data to calculate methane emissions from the landfill using an air dispersion model such as American Meteorological Society (AMS)/EPA Regulatory Model (AERMOD) or CalPUFF. There is no standardized method for obtaining the field methane measurements. Methane concentration from SEM events has been used (Huitric and Kong, 2006), as well as plume measurement (Goldsmith et. al. 2012).

Like Methane Measurement Methods B-2 and B-3, this method also requires the collection of extensive meteorological data, which must be collected contemporaneously with methane concentration data. Methane monitoring data and associated meteorology data are expensive to collect if the data are not already being collected for other purposes, and the use of methane monitoring data from a single monitoring event are only reflective of methane emissions during that event. Ongoing monitoring (e.g. plume measurement, stationary sensors) requires sophisticated equipment and many of the same considerations as Method B-3, including power and data management considerations.

Determination of emission rates from air dispersion modeling is not a regulatory requirement in any jurisdiction, though it has been used to demonstrate regulatory compliance in California. No standard method for reverse modeling has been developed, but methods have been proposed (Huitric and Kong, 2006). Air dispersion methods produce generally accurate results, but regulatory models tend to over predict impacts, which would lead to under predicting emissions. They also tend to be inaccurate when modeling impacts very close to area sources, such as landfills. The limitations of this method are associated with the limitations of the monitoring method used to obtain methane measurements. Air dispersion modeling costs will be in the high tens of thousands of dollars to low hundreds of thousands of dollars per event. Sampling costs are likely to scale proportionately with the size of the landfill.

Recommended Approach for Landfill Measurements

Flux chamber is the most well demonstrated method of methane flux measurement at landfills and should be considered as a method for confirming methane emission data. We also recommend the use of the pre-screening with SEM to reduce the number of sample locations needed. SCS also believes that eddy covariance and similar micrometeorological measurement methods show substantial promise for measuring methane emissions from landfills, but further development is needed, including making them more cost effective. The technology has been validated in other applications. The remaining challenges for broader utilization of eddy covariance in landfill methane measurement are cost and developing monitoring packages that can be used by less specialized users.

LANDFILL METHANE MONITORING

Landfill methane monitoring is the direct measurement of methane emissions from landfills on an ongoing or recurring basis without quantification of methane emissions. The categories summarized below are:

- Surface emission monitoring (Method C-1)
- Ground based or low altitude imaging (Method C-2)
- Satellite and aerial imaging (Method C-3)

Surface Emission Monitoring (Method C-1)

Surface emission monitoring (SEM) is the practice of using a portable methane meter near the landfill surface, while traversing the area of the landfill, to measure methane concentrations immediately above the landfill itself.

SEM monitoring is required by the EPA for most landfills generating more than 50 megagrams per year of non-methane organic compounds (NMOCs), changing to 34 megagrams per year with new regulations. When monitoring finds methane exceeding action levels, the landfill is required to take action to reduce methane emissions. California also has SEM requirements for landfills with an active GCCS, and the California regulatory requirements are more stringent than the EPA's. Ontario and British Columbia do not have SEM requirements. Quebec is the only province that requires SEM for landfills with operating landfill gas collection systems (generally landfills greater than 1,500,000 m^3 capacity or that receive more than 50,000 tonnes per year of waste).

The level of scrutiny applied with SEM and the cost to sites can be changed by adjusting the spacing of the traversal pathway, requiring both integrated and instantaneous monitoring, requiring the monitoring of landfill surface penetrations, adjusting monitoring frequency, and by adjusting any methane monitoring levels that require landfills to take action. The EPA currently requires that instantaneous SEM be performed on a quarterly basis with a spacing of 30 meters for a serpentine path across the landfill surface, and that landfills take action when an instantaneous methane concentration of 500 parts per million by volume (ppmv) is detected. For comparison, the state of California requires instantaneous and integrated SEM on a quarterly basis with spacing of 7.6 meters (25 feet), and requires corrective action at either 500 ppmv of instantaneous methane or 25 ppmv integrated (average concentration across a 50,000 square foot [4,645 square meter] grid) methane. Finally, monitoring requirements can require monitoring of specific features or locations. For example, the newest EPA requirements require that facilities monitor at all surface penetrations, which includes wellheads, vents, and permanent posts. The California regulation already requires penetration monitoring. Quebec requires SEM to be conducted at least 3 times a year, in the spring, summer and fall. This frequency may be reduced to once per year for areas under final cover if results of two years of SEM do not exceed the 500 ppmv threshold in any location.

The cost of implementing the California requirements is roughly three times higher than implementing EPA requirements. Quebec requires that surface instantaneous concentrations of methane remain below 500 ppmv, but does not specify a traversal frequency or spacing. Detailed monitoring requirements are described in EPA regulations (40 Code of Federal Regulations [CFR] Part 60 Subpart XXX) or California regulations (California Code of Regulations [CCR] Title 17 Article 4, Subarticle 6). SEM events can benefit sites by identifying leaks in cover and increasing LFG recovery for energy recovery.

Costs for SEM for small sites (smaller than 50 acres [20 hectares]) are driven by mobilization, equipment, and reporting rather than the size of the site. The cost to perform SEM at small sites is much higher per area than for large sites. For large sites, costs scale more closely with the size of the site. Costs range from the mid thousands of dollars to low tens of thousands of dollars per event.

The effectiveness of the monitoring is related to the spacing of the monitoring path. Tighter pathways are less likely to miss small locations with high methane emission rates. Requiring mitigation at lower monitoring thresholds will reduce methane emissions as well. However, tighter path spacing is closely related to the cost of monitoring. Making the monitoring more effective will increase costs. As noted, the EPA requires spacing of 30 meters, California requires spacing of 7.6 meters, and the cost of monitoring in California is roughly three times higher. Most, but not all, of the cost difference is driven by the spacing requirement.

SEM can be used at most landfills. Weather conditions impose some restrictions on its effectiveness. It cannot be performed on snow covered sites, and it should not be done immediately after a precipitation event. California requires that monitoring be performed when winds are less than five (5) miles per hour on average, and the new EPA regulation requires the use of a wind barrier when winds average more than four (4) miles per hour. Facilities that expect to have difficulty performing monitoring under these weather conditions can request alternative conditions from the regulatory agencies, and any regulation imposing a SEM requirement should allow sites to do the same.

Ground Based or Low Altitude Imaging (Method C-2)

Infrared (IR) cameras are cameras that are capable of seeing into frequencies that the human eye cannot detect but in which methane is visible. These types of cameras are already deployed in the oil and gas industry to screen for leaks in pipelines and other oil and gas infrastructure. They are not in common use in the solid waste industry, and there are application specific challenges that may need to be overcome before widespread adoption, but the technology is demonstrated in principle by widespread use in the oil and gas industry.

In landfill applications, IR cameras could be used by landfill personnel to screen for large methane emission points on the landfill surface or as part of the landfill GCCS. Drone-mounted IR cameras have the potential to monitor remote landfills or portions of the landfill that cannot be safely accessed for SEM. However, when high methane emissions are found, IR cameras may not be good at finding the source of methane emissions and personnel may be required to investigate the source with SEM equipment.

In addition to IR cameras, other optical technologies, such as hyperspectral imaging and thermal imaging, have application at landfills. Those applications are currently niche applications and are not used as methane monitoring, but they may have future application in monitoring programs. The discussion will focus on IR imaging because of its demonstrated use in other fields.

IR cameras are used to comply with the EPA regulations for leak detection and repair (LDAR) in the oil and gas industry. The characteristics of the emission sources in the oil and gas industry are not the same as those at a landfill. Methane leaks from oil and gas facilities tend to be localized hot spots like seams and holes in equipment. While cracks and fissures in landfill cover can lead to localized hot spots, methane emissions at landfills tend to be slow but over a large surface area.

IR cameras can be mounted, hand held, or drone mounted. This versatility means most sites should be able to find an application of IR cameras that is suitable for the site. Equipment and monitoring costs are in the high thousands of dollars to mid tens of thousands of dollars per event.

IR imaging is expected to be moderately to highly effective at finding local areas of high methane emissions and moderately effective at characterizing sitewide emissions. Imaging can get a sitewide overview relatively quickly and is unlikely to miss localized hot spots that SEM might miss. As technology improves, IR technologies may be able to see and accurately quantify low concentration leaks as this becomes more cost effective.

Satellite and Aerial Imaging (Method C-3)

This monitoring method is similar to Methane Monitoring Method C-2 in that it uses imaging from outside the visible range to detect methane, but it is practiced on a different scale. Methane Monitoring Method C-2 employs ground-based or low altitude (drone) cameras to look for methane hot spots, but satellite or aerial imaging uses high altitude or orbital imaging to get an overall picture of methane emissions from a landfill.

Aerial and orbital cameras have been demonstrated to be able to see substantial methane plumes, notably in the SoCal Gas Aliso Canyon leak. Similar distant imaging could be used to get a picture of the methane emissions at landfills, and several Southern California studies were able to see methane emissions from large landfills. However, the distance of the imaging would severely limit the utility of the imaging to determine precise locations of methane emissions or hot spots. This remote imaging does not currently provide a quantitative estimation of methane emissions or concentrations, but research and methodologies are being developed to establish quantitative measurements.

SCS determined that the cost and equipment required for this type of monitoring is not practical and the method should not be pursued for monitoring of individual sites. It is unlikely to match the effectiveness of Method C-2 for monitoring of individual sites. It does have limited application in monitoring large releases or regional methane emissions for research purposes.

State of the Monitoring Practice in Canada

Landfill methane monitoring is generally not practiced in Canada. Only Quebec has surface landfill methane standards, but the regulation does not describe the monitoring method or requirements.

Monitoring is primarily performed at the recommendation of a consultant on an as-needed basis. Based on SCS's experience and discussion with other landfill consultants who work in Canada, SEM procedures are derived from EPA methods. Ground based or high altitude imaging are not in common practice in Canada.

Recommended Approach for Landfill Monitoring

SCS believes that SEM is a well demonstrated and proven monitoring strategy for landfill emissions. SEM requirements can be balanced to achieve cost effective monitoring by adjusting the monitoring path spacing and the action level for required remedial action. Where only SEM monitoring threshold on landfills are specific, this may provide flexibility for individual landfills to determine what frequency is necessary to avoid emissions exceeding regulatory requirements or operational objectives.

SCS also believes that IR imaging is a promising technology that complements SEM. It is not as robustly demonstrated for landfill application as SEM, but it should be considered as an alternative or complement to SEM. IR imaging has the potential to quickly identify high methane emission points on landfills that could potentially be missed by SEM, while SEM has the ability to quantify the concentration of methane accurately at such hot spots. They could work well in concert, but the combined costs may make them prohibitive for many individual sites.

REFERENCES

Bogner, Spokas, and Corcoran, 2011. A Site-Specific Process-Based Model for Landfill CH4 Emissions Inclusive of Seasonal Soil Microclimate and CH4 Oxidation. (available at https://www.researchgate.net/publication/252994983_A_fieldvalidated_model_for_landfill_methane_emissions_inclusive_of_seasonal_methane_oxidation)

Goldsmith, Chanton, Abichou, Swan, Green, and Hater, 2012. Methane Emissions from 20 Landfills Across the United States Using Vertical Radial Plume Mapping. (available at https://www.ncbi.nlm.nih.gov/pubmed/22442934)

Huitric, R., and Kong, D. 2006. Measuring Landfill Gas Collection Efficiencies Using Surface Methane Concentrations, Solid Waste Association of North America (SWANA) 29th Landfill Gas Symposium, St. Petersburg, FL, 2006. (available at https://pdfs.semanticscholar.org/0992/1c2fcf87a7eec88750669a0dfaf31de41ab8.pdf)

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 3 – Solid Waste Disposal. (available at https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html)

National Council for Air and Stream Improvement (NCASI), 1999. Evaluation of the EPARecommended Approach to Predicting Air Emissions from Pulp and Paper Industry Landfills. (available at https://digitalcommons.calpoly.edu/cenv_fac/48/)

Radian Corp. 1986. Measurement of Gaseous Emission Rates from Land Surfaces Using an Emission Isolation Flux Chamber. User's Guide. (available at https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=ORD&dirEntryID=51253)

SWICS, 2007 Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills. (available at https://www.scsengineers.com/scs-white-papers/current-msw-industry-position-and-and-state-ofthe-practice-on-lfg-collection-efficiency-methane-oxidation-and-carbon-sequestration-in-landfillspresented-to-solid-waste-industry-for-climate-solu/)

SWICS, 2009. Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills version 2.2. (available at https://www.scsengineers.com/scs-white-papers/current-msw-industry-position-and-state-of-thepractice-on-lfg-collection-efficiency-methane-oxidation-and-carbon-sequestration-in-landfillsprepared-for-solid-waste-industry-for-climate-solution/)

SWICS, 2012. SWICS 2.2 Methane Oxidation Addendum 2012.

U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Air Quality Planning and Standards, 1998. Municipal Solid Waste Landfills. Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources. (available at https://www3.epa.gov/ttn/chief/ap42/ch02/index.html)

EXISTING LANDFILL EMM REGULATIONS

Methane Emissions from Municipal Solid Waste Landfills, California Air Resources Board. Title 17 CCR Article 4, Subarticle 6, Sections 95460 to 95476 (available at https://www.arb.ca.gov/cc/landfills/landfills.htm)

Mandatory Greenhouse Gas Reporting. Code of Federal Regulations, Part 98, Title 40, 2016. (available at https://www.ecfr.gov/cgi-bin/text-idx?SID=804afd617304d31dddef3df1c0a2591b&mc=true&node=sp40.23.98.hh&rgn=div6)

Standards of Performance for Municipal Solid Waste Landfills, U.S. EPA. 40 CFR Part 60, Subpart WWW. (available at https://www.ecfr.gov/cgi-bin/textidx?SID=804afd617304d31dddef3df1c0a2591b&mc=true&node=sp40.8.60.www&rgn=div6)

Standards of Performance for Municipal Solid Waste Landfills that Commenced Construction, Reconstruction, or Modification after July 17, 2014, U.S. EPA. 40 CFR Part 60, Subpart XXX. (available at https://www.ecfr.gov/cgi-bin/text-idx?SID=804afd617304d31dddef3df1c0a2591b&mc=true&node=sp40.8.60.xxx&rgn=div6)

Landfill Gas Management Regulation, BC. Statutes of BC (SBC) 2008 c. 20. (available at https://www2.gov.bc.ca/gov/content/environment/waste-management/garbage/landfills)

General Waste Management Regulation, Ontario. Regulation 232, Regulation 347. (available at https://www.ontario.ca/laws/regulation/980232 and https://www.ontario.ca/laws/regulation/900347)

Regulation for Respecting the Landfilling and Incineration of Residual Materials, Quebec. Environment Quality Act, Chapter Q-2, r. 19. (available at http://legisquebec.gouv.qc.ca/en/ShowDoc/cr/Q-2,%20r.%2019)

MODEL LINKS

British Columbia LFG Model (https://www2.gov.bc.ca/gov/content/environment/wastemanagement/garbage)/landfills)

IPCC Waste Disposal System Model (https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html)

LandGEM (https://www.epa.gov/catc/clean-air-technology-center-products#software)

California Landfill Gas Tool (https://www.arb.ca.gov/cc/landfills/landfills.htm)

CALMIM (https://www.ars.usda.gov/research/software/download/?softwareid=300)

Attachment 1 – Annotated List of EMM Methods

Number	General Category	Specific Implementations	Advantages	Disadvantages	Cost Range (In Canadian Dollars)
Emission Estimation Method A-1	FOD Models	IPCC model	Various levels of sophistication	Limited use of site data	High hundreds to low thousands
		LandGEM/AP-42	Possible to implement with simplified inputs	Site specific results can be unrepresentative of specific sites	
		California GHG Inventory/CARB model	Aggregate results tend to be accurate	Requires historic data what may not meet desired data quality.	
		EPA GHGRP Equation HH-1	Can be implemented with spreadsheet	Conditions for modeled site must be consistent with assumptions in model.	
		EPA GHG Inventory	Can be modified to account for gas collection (see Method 3)	Linked to waste characterization data.	
		Scholl Canyon model			
Emission Estimation Method A-2	Measured LFG Collection and Estimated Collection Efficiency	EPA GHGRP Equation HH-8	Relies on some site specific data.	Only applicable to sites that collect LFG	Low to mid thousands
		SWICS Methodology	Most required data is already being collected by sites with LFG collection	Inflexible models can incentive poor gas collection practice.	
		EPA GHG Inventory			
Emission Estimation Method A-3	FOD Modeling with Measured LFG Collection	EPA GHGRP Equation HH-6	Relies on some site specific data.	Modification of Method 1 for sites with LFG collection, with all associated disadvantages.	Low to mid thousands
		California GHG Inventory	Most required data is already being collected by sites with LFG collection		
		EPA GHG Inventory			
Emission Estimation Method A-4	Non-FOD Models	CALMIM	Alternative approach when FOD yields unreasonable results.	Not widely implemented	Low to mid thousands
			Possible to implement with limited inputs.	Can require data not typically collected by a landfill (e.g. soil parameters, climate data)	
				Limited use of site data	
				Assumptions conflict with Method 1, which is more widely accepted.	
Methane Measurement Method B-1	Flux Chamber Testing	EPA Isolation Flux Method	Direct measurement of emission rates.	Requires extrapolating small sample area to large landfill area.	Tens of thousands to hundreds of thousands.
				Expensive	
				Revisions to EPA method are not formally adopted or reviewed for regulatory purposes.	
				Provides only a snapshot of emissions at time of measurement.	
Methane Measurement Method B-2	Plume Measurement	EPA Method OTM 10	Direct measurement of emissions.	Extremely expensive.	Hundreds of thousands per event.
				Requires calm weather conditions.	
				Provides only a snapshot of emissions at time of measurement.	
				Stationary monitoring may not be suitable for dynamic source locations.	
				Requires specialized skills.	
Methane Measurement Method B-3	Stationary Path Measurement	Eddy Covariance	Direct measurement of emissions.	Provides only a snapshot of emissions at time of measurement.	Hundreds of thousands per site.
			Off-the-shelf packages becoming available.	Extremely expensive.	
				Stationary monitoring may not be suitable for dynamic source locations.	
				Requires specialized skills.	

Number	General Category	Specific Implementations	Advantages	Disadvantages	Cost Range (In Canadian Dollars)
Methane Measurement Method B-4	Dispersion Modeling Approaches	Research uses only	Adapts methods likely to be utilized in solid waste industry.	Provides only a snapshot of emissions at time of measurement.	High tens of thousands to low hundreds of thousands per event.
				Relies on air dispersion model's accuracy	
				Requires representative meteorological data.	
				Expensive	
Methane Monitoring Method C-1	Surface Emission Monitoring	Landfill NSPS	Many ways to control thoroughness of monitoring (e.g. frequency, spacing, integrated vs. instantaneous, and concentration limits)	Cannot practically cover the entire landfill.	Mid thousands to low tens of thousands per event.
		California LMR	Can be integrated with requirements to reduce methane concentrations.	Requires ongoing monitoring to be effective.	
			Thoroughly demonstrated and well established.	Does not scale well for small sites.	
Methane Monitoring Method C-2	Ground Based or Low Altitude Imaging	FLIR	Monitoring can be performed remotely.	Does not pinpoint source of methane emissions.	High thousands to low tens of thousands per event.
		Hyperspectral imaging	Quickly gets overview of areas monitored	May require additional investigation to find/correct leaks.	
			Demonstrated in oil and gas field.		
			Multiple deployment options.		
Methane Monitoring Method C-3	Satellite and Aerial Imaging	Aliso Canyon pictures	Provides overview of site emissions.	Not demonstrated for small sources.	Tens of thousands to hundreds of thousands.
		Landfills in Los Angeles Area	Only sees hot spots.	Cannot pinpoint leak sources.	
				Cannot quantify emissions or concentrations.	
				Expensive.	
				May have interferences with other nearby methane sources.	
				Requires coordination with satellites or aerial imaging sources.	

Note: Additional specific implementations exist. Generalized implementations are available.

AP-42 – US EPA Compilation of Air Emissions Factors C&T –
cap and trade
EPA – United States Environmental Protection Agency FLIR –
Forward looking infrared
GCCS – LFG collection and control system
GHG – Greenhouse gas
GHGRP – Greenhouse Gas Reporting Program
IPCC – Intergovernmental Panel on Climate Change
IR - Infrared
LandGEM – Landfill Gas Emission Model LFG –
Landfill gas
LFG – Landfill gas
LMR – Landfill Methane Rule OTM –
Other test method ppmv – Parts per
million by volume SEM – Surface
Emission Monitoring
SWICS – Solid Waste Industry for Climate Solutions

METHANE ESTIMATION METHODS

Methane Estimation Method A-1 – First Order Decay (FOD) Modeling

This method uses a FOD model to calculate methane generation from waste placed in a landfill. All models using this methodology require the input of waste mass over time, typically annually, and decay parameters based on the waste type and/or climate. The United States Environmental Protection Agency (EPA) Landfill Gas (LFG) Emission Model (LandGEM) is one of the simplest, and requires only the input of was mass by year and the decay rate. LandGEM was developed from earlier FOD models, such as the Scholl Canyon model, which are no longer in wide use. The Intergovernmental Panel on Climate Change (IPCC) model allows for increasing levels of sophistication of inputs, including characterization of waste inputs by year into eight (8) categories. The most sophisticated versions of FOD models utilize decay parameters specific to each year, but this practice is not in common use or implemented in most existing spreadsheets.

Methane Estimation Method A-2 – Measured LFG Collection and Estimated Collection Efficiency

This method relies on measuring the amount of methane in collected LFG and estimating the collection efficiency of a landfill's LFG collection and control system (GCCS) to calculate the emission of methane from the landfill. This reliance on measurement of collected methane means that this method cannot be implemented at sites without a GCCS.

The collection efficiency for a site can be estimated in various ways, including assuming a fixed collection efficiency for all sites with a GCCS, determining collection efficiency based on landfill cover type, and engineering estimates of collection efficiency. Methodologies allowing for professional judgement may incentivize overestimation of collection efficiency, especially if associated with combination with a cap and trade (C&T) program. Methodologies using a fixed collection efficiency (e.g. 75 percent for all landfills with a GCCS) may incentivize under collection of LFG, which would result in lower calculated emissions.

Much of the data required by this method is typically collected by landfills with a GCCS, but sites may require additional monitoring to improve or demonstrate that data quality is sufficient or that data are representative.

The costs shown for the implementation reflect costs for some additional monitoring of collected LFG and calculation of emissions.

Methane Estimation Method A-3 – First Order Decay (FOD) Modeling with Measured LFG Collection

This method relies on measuring the amount of methane in collected LFG and modeling of methane generation to calculate the emission of methane from the landfill. The modeling of methane generation is typically done with a FOD model, as in Methane Estimation Method 1. Measured methane collection is deducted from the modeled methane generation, with the difference assumed to be emitted to the atmosphere.

Much of the data required by this method is typically collected by landfills with a GCCS, but sites may require additional monitoring to improve or demonstrate that data quality is sufficient or that data are representative.

The accuracy of this method is limited by the accuracy of the FOD model, and cases where collected methane exceed the modeled methane generation highlight the limitations of the FOD model.

Methane Estimation Method A-4 – Non First Order Decay (FOD) Modeling

FOD modeling is the standard way of modeling methane emissions from landfills, but alternative models have been proposed. These models have not been widely implemented in regulatory or inventory practice and are generally considered research models. The most prominent of these models is the California Landfill Methane Inventory Model (CALMIM), which was developed for use in California, but is supported by the EPA.

METHANE MEASUREMENT METHODS

Methane Measurement Method B-1 – Flux Chamber Testing

This method requires sampling the flux (emission rate per area) of the surface of the landfills. The sampling apparatus for flux measurement is small (typically one meter square), so sampling the entire surface of a landfill is impractical and sampling methods must be used. The EPA developed a flux sampling method applicable to landfills, but the number of samples required for even small landfills is impractical.

Alternative sample screening and selection methods have been developed by interested parties to reduce the number of required samples and retain the number of samples. These alternate methods typically require using a hand held device to measure the concentration of methane above the landfill surface.

The cost for this method reflects sampling with the reduced number of sample locations and not the EPA method.

Methane Measurement Method B-2 – Plume Measurement Methods

Optical plume measurement uses a ground based optical sensor to measure the methane plume coming from a landfill. Those plume measurements are then used to calculate the methane emission rate from a landfill. There is currently no standardized optical sensor method. The EPA has published Other Test Method 10 (OTM 10), but it has generally fallen out of use and is not regarded as practical or accurate enough for regular use.

These methods require sophisticated sensor setups, including sensors, meteorological monitoring, and computer software. Due to the large cost, specialized knowledge required to operate, and restrictive operating conditions, ground based optical sensor methods have fallen out of favor.

Methane Measurement Method B-3 - Other Optical Sensor Methods

Other optical sensor methods use methane concentration measurements along few paths rather than measuring many paths to determine the size of a plume. The most common of these methods is eddy covariance. In these methods, the concentration of methane between fixed points is used to calculate the methane flux from a source.

Like plume measurement methods, eddy covariance and other optical sensor methods require a substantial amount of equipment to function. The method requires measurement of methane concentrations and meteorology, as well as extensive computer processing. These methods are not in common use, but as their use has increased, off-the-shelf packages have become available.

Methane Measurement Method B-4 – Air Dispersion Modeling Approaches

Air dispersion emission calculation methodologies use field measurement of methane concentration data and contemporaneous meteorology data to calculate methane emissions from the landfill using an air dispersion model such as American Meteorological Society (AMS)/EPA Regulatory Model (AERMOD). There is no standardized method for obtaining the field methane measurements, but optical sensors and modified surface emission monitoring with a portable device have been used.

Like Methane Measurement Methods 2 and 3, this method also requires the collection of extensive meteorological data, which must be collected contemporaneously with the methane concentration data. Unlike those methods, the skillset required for this method are more likely to exist within the solid waste industry already.

Once field measurements are obtained, the dispersion model is run and calculations are used to calculate the emission rate that would have resulted in the measured concentration.

METHANE MONITORING METHODS

Methane Monitoring Method C-1 – Surface Emission Monitoring

Surface emission monitoring (SEM) is the practice of using a portable methane meter near the landfill surface, while traversing the area of the landfill, to measure methane concentrations immediately above the landfill itself. SEM monitoring is required by the EPA for most landfills generating more than 50 megagrams per year of non-methane organic compounds (NMOCs), changing to 34 megagrams per year with new regulations. When monitoring finds methane exceeding action levels, the landfill is required to take action to reduce methane emissions.

The level of scrutiny applied with SEM can be changed by adjusting the spacing of the traversal pathway, requiring both integrated and instantaneous monitoring, requiring the monitoring of landfill surface penetrations, adjusting monitoring frequency, and by adjusting any methane monitoring levels that require landfills take action. The EPA currently requires that instantaneous SEM be performed on a quarterly basis with a spacing of 30 meters, and that landfills take action when an instantaneous methane concentration of 500 parts per million by volume (ppmv) is detected. For comparison, the state of California requires instantaneous and integrated SEM on a quarterly basis with spacing of 7.6 meters (25 feet), and requires corrective action at either 500 ppmv of instantaneous methane or 25 ppmv integrated methane. The cost of implementing the California requirements is roughly three times higher than implementing EPA requirements. Quebec requires that surface instantaneous concentrations of methane remain below 500 ppmv, but does not specify a traversal frequency or spacing.

Costs for SEM for small sites (smaller than 50 acres [20 hectares])are driven by mobilization, equipment, and reporting rather than the size of the site. The cost to perform SEM at small sites is much higher per area than for large sites.

Methane Monitoring Method C-2 – Ground Based or Low Altitude Imaging

Infrared (IR) cameras are cameras that are capable of seeing into frequencies that the human eye cannot detect but in which methane is visible. These types of cameras are already deployed in the oil and gas industry to screen for leaks in pipelines and other oil and gas infrastructure. They are not in common use in the solid waste industry, and there are application specific challenges that may need to be overcome before widespread adoption, but the technology is demonstrated in principle.

In landfill applications, IR cameras could be used by landfill personnel to screen for large methane emission points on the landfill surface or as part of the landfill GCCS. Drone-mounted IR cameras have the potential to monitor remote landfills or portions of the landfill that cannot be safely accessed for SEM. However, when high methane emissions are found, IR cameras are not good at finding the source of methane emissions and personnel may be required to investigate the source with SEM equipment.

In addition to IR cameras, other optical technologies, such as hyperspectral imaging and thermal imaging, have application at landfills. Those applications are currently niche applications and are not used as methane monitoring, but they may have future application in monitoring programs.

Methane Monitoring Method C-3 – Satellite or Aerial Imaging

This Monitoring Method is similar to Methane Monitoring Method C-2 in that it uses imaging from outside the visible range to detect methane, but it is practiced on a different scale. Methane Monitoring Method C-2 employs ground-based or low altitude (drone) cameras to look for methane hot spots, but satellite or aerial imaging uses high altitude or orbital imaging to get an overall picture of methane emissions from a landfill.

Aerial and orbital cameras have been demonstrated to be able to see substantial methane plumes, notably in the SoCal Gas Aliso Canyon leak. Similar distant imaging could be used to get a picture of the methane emissions at landfills. However, the distance of the imaging would severely limit the utility of the imaging to determine precise locations of methane emissions or hot spots. This remote imaging does not currently provide a quantitative estimation of methane emissions or concentrations, but research and methodologies are being developed to establish quantitative measurements.