

Practical Methods for Measuring Landfill Methane Emissions

By Jeremy K. O'Brien, P.E.

Landfills have been identified by regulators and policy-makers as significant sources of greenhouse gas (GHG) emissions. Historically, the determination of methane emission rates has been based on assumptions regarding LFG generation rates, LFG collection system efficiencies, and methane oxidation in landfill cover soils.

Recent regulatory requirements and policy directives are putting more pressure on landfill managers to better estimate their facility GHG emissions based on field measurements rather than modeled generation rates.

Taking field measurements of methane emissions at landfills is challenging. Landfills can spread over tens to hundreds of acres and surface area emissions vary substantially due to differences in topography, types of waste disposed, the types, extent, and condition of cover systems (daily, intermediate, final) and the in-place LFG management systems, if any. From a regulatory perspective, landfills are considered an "area" source (versus point source) where emissions vary spatially and temporally.

The practice has experienced a number of recent breakthroughs in the areas of measurement technologies, analytical methods to allocate emissions to the entire footprint, and the development of standard operating procedures for field assessments. All of these contribute to the ability of the landfill manager to more accurately quantify fugitive LFG emissions.

This article presents highlights from a recent SWANA Applied Research Foundation (ARF) report, "Practical Methods for Measuring Landfill Methane Emissions and Cover Soil Oxidation." This report was prepared by the SWANA ARF staff with input and guidance provided by the Fiscal Year (FY) 2013 ARF Disposal Group Subscribers, who are listed in Table 1. (The SWANA Applied Research Foundation was founded in 2001 with the purpose of conducting col-

lectively defined and funded applied research on pressing solid waste issues. It is funded by local governments and other organizations that contribute a "penny per ton" of waste managed to the foundation on an annual basis. For more information on the SWANA Applied Research Foundation, please contact Jeremy O'Brien, director of applied research, SWANA, 301-585-2898.)

Several field measurement methods are used to estimate methane emissions from

CONTENTS

- METHANE EMISSIONS
- SWANADVOCATE
- SWANA ELECTIONS
- YOUNG PROFESSIONALS

TABLE 1-1

SWANA Applied Research Foundation – FY 2013 Disposal Group Subscribers

Jurisdiction	Representative	Title
Chester County Solid Waste Authority (PA)	Robert Watts	Executive Director
Delaware County Solid Waste Authority (PA)	Joseph Vasturia, PE	Chief Executive Officer
Delaware Solid Waste Authority (DE)	Richard Watson, PE, BCEE	Chief Operating Officer
City of Denton (TX)	Scott Lebsack	Assistant Director of Solid Waste
Golder Associates Inc.	Kevin Brown, PE	Senior Consultant and Principal
Kent County (MI)	Douglas Wood	Director, Department of Public Works
King County (WA)	Kevin Kiernan	Solid Waste Division Manager
Lancaster County Solid Waste Management Authority (PA)	Brooks Norris	Senior Manager, Technical Services
Los Angeles County Sanitation Districts (CA)	Mario Iacoboni	Supervising Engineer
Mecklenburg County (NC)	Joseph Hack, QEP	Contracted Operations Manager
Metro Waste Authority (IA)	Jeff Dworek	Director of Operations
New River Solid Waste Association (FL)	Darrel O'Neal	Executive Director
North Carolina SWANA Chapter	Joe Readling, PE	Vice President - HDR Engineering, Inc.
Solid Waste Authority of Palm Beach County (FL)	Mark Hammond	Executive Director
SCS Engineers	Robert Gardner, PE, BCEE	Senior Vice President
Solid Waste Authority of Central Ohio (OH)	Rick Dodge	Chief Operating Officer
City of Tucson (AZ)	Jeff Drumm	Environmental Manager
Waste Commission of Scott County (IA)	Kathy Morris	Director
Winston-Salem City/County Utilities (NC)	Jan McHargue, PE	Solid Waste Administrator

the surface of a landfill:

- Vertical radial plume mapping (VRPM)
- Tracer gas correlation
- Flux chamber
- Micrometeorological
- Differential absorption LiDAR (DIAL).

The five methods can be grouped into two categories, according to approach:

- **Surface factor methods**—The VRPM, flux chamber, and micrometeorological methods are designed to measure methane emission rates from either points (flux chambers and micrometeorological) or areas (VRPM) of the landfill surface. These measurements are used to develop an average emission rate for a limited area, which can be extrapolated to determine emissions for the entire landfill surface.
- **Mass emission methods**—The mass emission methods (tracer gas correlation and differential absorption LiDAR) are designed to measure methane emissions rates from the entire landfill surface. The utility of these methods in estimating landfill methane emissions from field measurements has been assessed through a number of field investigations over the past several years (Table 2).



Figure 1

VERTICAL RADIAL PLUME MAPPING (VRPM) METHOD

The vertical radial plume mapping (VRPM) method is a methane flux measurement method specified in the EPA's "Other Test Method 10" (OTM-10). OTM-10 uses optical remote sensing (ORS) instruments to quantify emissions from area sources such as landfills.

The VRPM method uses an ORS instrument to obtain path-integrated emission concentration data along multiple optical beam measurement paths. (ARCADIS U.S. Inc. *Quantifying Methane Abatement Efficiency at Three Municipal Solid Waste Landfills*. EPA/600/R-12/003. Research Triangle Park, NC: US EPA Office of Research and Development, January 2012.) Measurement paths are defined by the distance between the scanning instrument and a reflecting mirror placed some distance away.

The VRPM method measures the mass of an emission, such as

Field Measurement Methods to Determine Landfill Methane Emissions

No.	Method	Field Investigation	Timeframe	Number of Sites
1	Vertical Radial Plume Mapping (VRPM)	Waste Management, Inc. Field Test Program	2006 - 2010	20
		EPA Field Test Program	2009 - 2010	3
2	Tracer Gas Correlation	WM Field Test Program	2009 - 2010	10
3	Flux Chamber	County Sanitation Districts of Los Angeles County (Districts)	2010 - 2013	3
4	Micrometeorological	EREF Field Methods Comparison Study	2008	2
5	Differential Absorption LiDAR	EREF Field Methods Comparison Study	2008	2

Table 2

methane, that travels through a vertical plane established downwind of the area generating the emission. The vertical plane is defined as the plane in which the laser beams are emitted from the ORS instrument and reflected back to the instrument as shown in Figure 2.

The laser beam characteristics are changed by their interactions with emissions along the path. Documenting the changes enables the instrument to estimate the quantity (i.e., mass) of the emissions. These data, along with meteorological data collected at the same time, are then analyzed using vertical and horizontal radial plume mapping methods to estimate the total mass per second passing through the plane. This flux is reported in grams per second.

To measure the emissions, an open-path tunable diode laser (OP-TDL) is used as the ORS instrument. This instrument emits radiation at a particular wave-length in the infrared region when an electrical current is passed through it. The light wavelength depends on the current and therefore can be varied to allow scanning over an absorption feature associated with the emission being measured.

The laser signal is transmitted from a single telescope to a retro-reflecting mirror target, usually set up between 100 meters (109 yards) and 1,500 meters (1,640 yards) from the source. The returned light signal is received by the single telescope and directed to a detector. By analyzing the number of return signals that show the methane absorption feature, the instrument provides instantaneous, path-integrated methane concentration data.

Waste Management Inc. (WM), partnered with academic institutions (Florida State University and North Carolina State University), other companies (Veolia Environmental Services, the Environmental Research and Education Foundation, and the EPA), from 2006 to 2010 to evaluate measurement and modeling techniques for the quantification of methane emissions and oxidation. (Chanton, J., Langford, C., Green, Hater, G., Abichou, T. and Swan, N. *Landfill Methane Emissions and Oxidation: Recent Developments towards Systematic Measurement and Quantification*. Proceedings: SWANA's 2011 Landfill Gas Symposium. Silver Spring, MD: SWANA, 2011.)

Through this program, studies were conducted at 20 landfills in a variety of climates. Emission measurements were made both with the static flux chamber method and the VRPM method specified in the EPA's OTM-10. WM and EPA entered into an agreement to refine the OTM-10 through this program.

In the early stages of testing, WM found that the VRPM method provided good quantitative concentration measurements. However, it was unable to give satisfactory estimates of surface emissions based on the analysis and scaling of the data. The reason for this was that the emission "flux" could not be traced to a specific surface area of the landfill that produced the emissions. As a result, the flux data

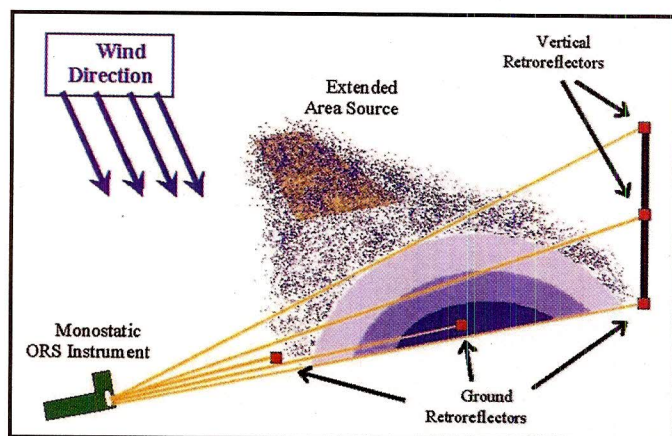


Figure 2

(measured in grams of methane per second) could not accurately be converted to landfill emissions estimates (reported in grams of methane per square meter per day).

WM submitted a formal comment on the method's inadequacies, then worked with EPA on scaling the procedure to more accurately estimate the flux per unit area. After another two years of testing, WM reported that the "area contributing to flux" (ACF) could be estimated. Several other key setup and operating variables were also defined. The VRPM method can now be used to estimate complete landfill emissions and is mature enough for the user to be able to recognize its biases and limitations.

As an additional result of the extensive site testing of the VRPM method, WM concluded the cost per study event was too high for the VRPM technique to be used as a routine monitoring tool.

TRACER GAS CORRELATION METHOD

The tracer gas correlation method (TGCM) is another laser-based emissions measurement method tested in the WM field test program. In the TGCM method, an optical remote-sensing laser is placed downwind of the landfill. As the name implies, a tracer gas is released from locations on the landfill surface, and the concentrations of both the tracer gas and methane are measured using the laser device. A schematic of the TGCM is provided below.

Two types of tracer gas correlation measurements—mobile and stationary—can be performed with this method. In the mobile approach, a "cavity ring down" laser (CRDS) is mounted in a vehicle and driven back and forth across the plume downwind of the landfill. In the stationary approach, the laser is set up at a single location downwind of the plume. In both approaches, a tracer gas such as high-purity acetylene or nitrous oxide gas is released from one to three locations on the landfill surface using computerized mass flow controllers.

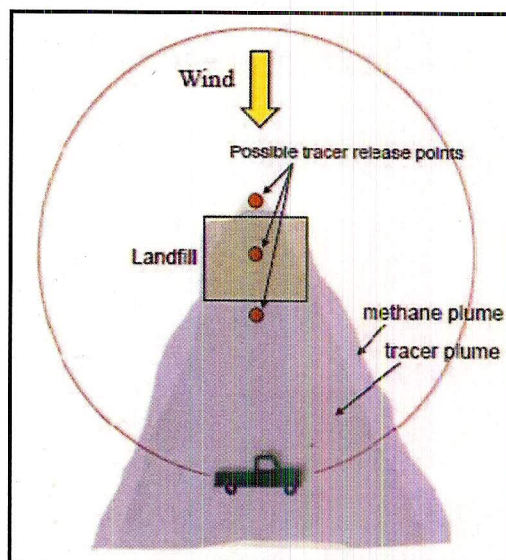


Figure 3

In the WM field test program, the CRDS unit was mounted in a full-size pickup truck fitted with an external snorkel for gas sample collection. The analyzer was integrated with a GPS system and a compact weather station. Concentration, position, and meteorological data were recorded in a time-synchronized data file while the truck was in motion or, alternatively, at a single location downwind of the landfill.

After a calibration check, mobile transect measurements were made by driving the analyzer along roads located around landfill. Continuous measurements of acetylene and methane concentration were recorded as the analyzer made transects through the plumes.

In the TGCM, the emission rate of methane is calculated as the product of the release rate of the tracer and ratio of integrals of the concentrations of acetylene and methane in the plume transects as shown in following equation:

$Q_m = Q_t \times \Delta C_m / \Delta C_t$, where

$Q_m = \text{CH}_4 \text{ emission rate}$

$Q_t = \text{Tracer gas release rate}$

$\Delta C_m = \text{CH}_4 \text{ observed in the plume relative to the background concentration}$

$\Delta C_t = \text{Tracer concentration in the plume relative to the background concentration.}$

WM used the TGCM more than 25 times at 10 different landfills in 2009 and 2010. Following this test program, WM concluded the TGCM was a sensitive and useful method of measuring ambient air concentrations of methane. It also found the cost of the TGCM method to be one-third to one-half the cost of the VRPM approach

FLUX CHAMBER METHOD

The flux chamber method is the most commonly used technique to measure gas emission rates from soils and gas fluxes from water surfaces. (Shan, J., Iacoboni, M. and Ferrante, R. *Estimating Greenhouse Gas Emissions from Three Southern California Landfill Sites*.

Proceedings: SWANA's 2013 Landfill Gas Symposium. Silver Spring, MD: SWANA 2013.) The EPA reports that most of the existing data available to evaluate fugitive emissions from landfills are based on flux chamber measurements. (ARCADIS U.S. Inc. *Quantifying Methane Abatement Efficiency at Three Municipal Solid Waste Landfills*. EPA/600/R-12/003. Research Triangle Park, NC: US EPA Office of Research and Development, January 2012.)

The flux chamber method involves sealing a precisely measured chamber above a gas-emitting surface so emissions are trapped in the chamber where their accumulation can be monitored. This technique provides a relatively simple way to measure gas exchange between cover soils and has been applied by many

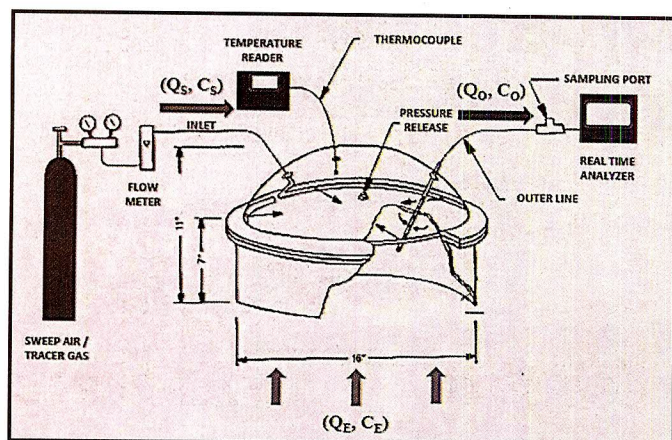


Figure 4

research groups around the world on both small and large landfills. A schematic of a dynamic flux chamber is provided below.

The flux chamber method was used by the County Sanitation Districts of Los Angeles County (the Districts) to conduct a study of methane and nitrous oxide emissions from three of its landfills. (Shan, J., et al, 2013.)

The objective of the study, conducted from 2010 through 2013, was to quantify landfill GHG (i.e., methane and nitrous oxide) emission rates at three active landfills in Southern California and to use the emission results to evaluate the performance of the gas collection systems at each landfill.

Emission rate measurements were conducted in accordance with EPA recommendations. (Kienbusch, M. *Measurement of Gaseous Emissions Rates from Land Surfaces Using an Emission Isolation Flux Chamber—User's Guide*. EPA 600/8-86/008. US EPA, 1986.) The Districts reported the technology to be the EPA's preferred testing technique for the direct measurement of volatile compound vapor emissions and identified it as one of the most promising techniques for the direct measurement of gas emissions from landfills.

The Districts found using flux chambers to measure LFG emissions to be challenging as a result of the inherently large surface areas and the heterogeneous nature of most landfill sites. To obtain representative and reliable data, the Districts identified random sample locations to systematically determine representative coverage over existing surface gas monitoring grids at each landfill.

Testing grids were randomly selected by running a random number generator over existing surface monitoring grids at each landfill. Each selected grid was tested for both methane and nitrous oxide in order to obtain representative fluxes. Ideally, each individual testing location would have been at the center of a grid; however, the flux chamber location at times varied according to such site-specific conditions as accessibility, irregular terrain (slopes), and landfill operations.

Field measurements of surface gas fluxes were taken using surface emission isolation flux chambers at each location. The overall emission rate and total emissions were estimated through a statistical analysis of the large number of field measurements.

Figure 5 shows the methane emission rates measured on the three landfill sites, showing different cover types (daily cover and interme-

diate and final cover—and site-average values.

The Districts observed that the majority of the measurements were in the low flux range of less than 500 mg/(m² x d), which represented more than 80% of the entire landfill surface area. On the other hand, a small portion of the measurements, from areas covering less than 20% of the landfill surface, recorded relatively high methane emission rates. These smaller areas with high emissions accounted for the major portion of the actual methane emissions for the entire site.

This observation is consistent with previous findings that landfill methane emissions are affected by small area point sources such as surface cracks, holes, or dead zones where the gas may not be collected as effectively. This finding also supports the usefulness of the surface methane concentration monitoring method as an effective method for detecting these emissions. In contrast, area methods (such as the OTM-10 and TGCM) provide only an average emission rate for an entire area.

The study results indicated that all daily cover areas emitted significantly more methane than intermediate or final cover areas. The Districts offered two explanations:

- Daily cover is thinner than intermediate and final cover.
- Landfill areas under daily cover lack LFG collection wells and trenches, both of which are added after lifts are completed.

The Districts concluded the study demonstrated that the surface flux-chamber method can be an effective tool for quantifying landfill surface GHG emissions.

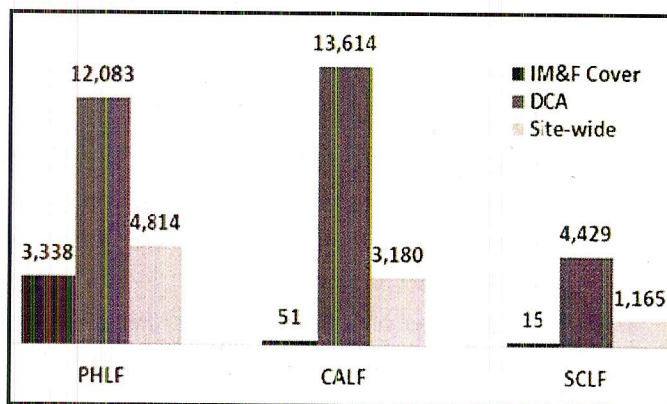


Figure 5

MICROMETEOROLOGICAL METHOD

The micrometeorological field measurement method for methane emissions is based on the analysis of turbulent vertical eddy currents that exist in the lowest 50 meters of the atmosphere. (Wong, C. "A Summary of Available Technologies for the Measurement of Fugitive Methane Flux from Landfills." Paper presented at the SWANA 24th Northwest Regional Solid Waste Symposium, April 1–3, 2009: Richmond, B.C. Canada.) This analysis is conducted using the eddy covariance technique, which measures and calculates vertical turbulent fluxes within atmospheric boundary layers (http://en.wikipedia.org/wiki/Eddy_covariance. Accessed on 12/27/13). The method analyzes high-frequency wind and scalar atmospheric composition data to determine fluxes of these properties.

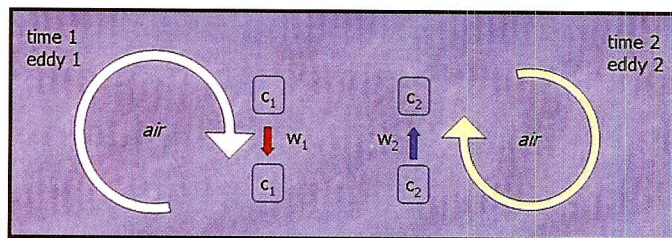


Figure 6

The eddy covariance technique is illustrated in Figure 6. (Drawing of eddies passing measurement point. Original PowerPoint image created by George Burba.)

In the figure, at one location on a measurement tower (not shown) at Time 1, Eddy 1 moves air parcel c_1 down at the speed w_1 . Then, at Time 2, Eddy 2 moves parcel c_2 up at the speed w_2 . Each parcel has gas concentration, pressure, temperature, and humidity. If these factors, along with the speed are known, the flux in gas concentration can be determined.

For example, if the methane concentration in Eddy 1 at Time 1 is measured, and the same is done for Eddy 2 at Time 2 at the same measurement point, the vertical flux of methane at this point over the time interval (Time 2–Time 1) can be calculated. In this way, vertical flux can be represented as a covariance of the vertical wind velocity and the concentration of methane.

The eddy covariance technique requires an instrument that can measure the gas concentration of interest (e.g., methane) at a very high frequency, typically at 10 to 30 hertz (cycles per second.) Of equal importance, the data logger must be able to record at these high frequencies and must be linked to the wind instrument device, which is typically an ultrasonic Doppler anemometer.

The micrometeorological method normally requires flat terrain over a large area and is based on the assumption that emissions are relatively uniform over the surface. As the method is based on point sampling, at the time of the study, it was uncertain how well the measurements could represent the entire landfill surface.

In 2008, the Environmental Research and Education Foundation (EREF) funded a study to compare the effectiveness of the five field measurement methods available for measuring landfill methane emissions. (Babilotte, A. *Field Comparison of Methods for Assessment of Methane Fugitive Emissions from Landfills*. Raleigh, NC: Environmental Research and Education Foundation, January 2011.) The study, which was conducted by the Veolia Environment Research and Development Center in collaboration with WM and Veolia Environmental Services of North America, was carried out at the WM Metro Recycling and Disposal Facility (Metro Landfill) and the Veolia Emerald

Park landfill, both of which are located in Franklin, WI. Field testing was conducted from September 29 through October 11, 2008.

Micrometeorological measurements were made at four different locations at the Metro Landfill. Two of the locations were in areas where either intermediate or final covers had been installed; two were in the active areas. The height of the measurement tower ranged from 3.9 to 6.7 meters.

Metro Landfill micrometeorological method field test results are presented in Table 3. Emissions from the areas with final cover in place were extremely low while those from the areas of the landfill with daily or intermediate cover were two orders of magnitude higher.

DIFFERENTIAL ABSORPTION LIDAR METHOD

The DIAL method measures the wind and contaminant concentration profiles through the full height of a plume and integrates the concentration and wind speed with respect to its height above ground surface. A schematic of the DIAL method is provided in the Figure 7.

In the DIAL method, a pulsed laser beam is sent out into the atmosphere, and small proportions of the light are backscattered to a detector by particles along the beam path. The dust particles and aerosols in the plume are used as reflectors for the laser beams. Laser light is emitted in short pulses and the measurement of the time required for the light to return to the source enables the technology to determine the location of the measured concentration in the plume being analyzed.

Multiple concentration measurements can be made along different lines of sight, which are then combined to produce two-dimensional concentration maps. A vertical scan of a landfill plume can be combined with wind data to calculate the methane flux emanating from a landfill surface. The mass balance method using the DIAL laser technology is arguably the most accurate method for determining methane emissions from landfill surfaces because it provides a complete concentration map

Summary of Micrometeorological Method Field Test Results - Metro Landfill

Landfill Cover	Approximate Area Investigated (m ²)	Total Area	Percent of Area Investigated	Methane Emission Rate (g/m ² /day)
Final Clay Cover	125,000	367,333	27%	5.8
Final Composite Cover		88,514		1.2
Intermediate Cover	73,000	92,497	39%	116.6
Daily Cover		97,808		113.2
TOTAL	198,000	646,152	30%	--

Table 3

Summary of DIAL Method Field Measurements - Emerald Park Landfill

Methane Surface Emissions (kg/hour)	Total Site Emissions	Phases 5 and 6	Phases 1 and 2	Phases 2, 3, and 4
Average	314	285.2	9.7	21.5
Standard Deviation	63	62.6	2.5	8.5
SD/Average	20.1%	21.9%	25.8%	39.5%

Table 4

of the plume. The Alberta Research Council concluded that the method is accurate to within about -18% to +5% (Wong, C., 2009).

The DIAL method was evaluated at two landfills during the EREF field methods comparison study. At each landfill, emission fluxes were measured by scanning DIAL laser beams through a vertical plane downwind of the source area and measuring the total concentration of methane above background levels along the plane. Wind data collected simultaneously with the measurements were also used to determine the methane emissions from the source area.

DIAL equipment was located on top of the Emerald Park Landfill. The mast used to measure wind speed and direction was 11 meters in height and was located on the top of Phase 4 of the landfill.

Three different vertical planes were established to calculate the landfill's methane emission rate. One plane was located in the northeast quadrant and was used to measure emissions from landfill phases 1, 2, 3, and 4. A second plane was located east of the site and used to measure emissions from phases 5 and 6.

Table 4 provides a summary of the methane emission measurements made with the DIAL method at the Emerald Park Landfill. The standard deviation from the average emission rate was calculated to be 20.1%.

COMPARISON OF METHODS

The EREF field methods comparison study report appendix presented a comparative assessment of the methods evaluated in the project (Babilotte, A., 2011). Table 5 provides a summary comparison of the five field methods for measuring landfill methane emissions, drawing

Summary of Field Investigation Findings Regarding Landfill Methane Field Measurement Methods

Method	Type	Stage of Development	Accuracy	Degree of Complexity	Equipment/Personnel Requirements
Vertical Radial Plume Mapping	Surface Factor Method	Not As Established	Low - Medium	Moderate	High
Tracer Gas Correlation	Mass Emission Method	Well-Established	High	Moderate	Moderate
Flux Chamber	Surface Factor Method	Well-Established	Low	Low	Low
Micrometeorological	Surface Factor Method	Well-Established	Low	Moderate	Moderate
Differential Absorption LIDAR	Mass Emission Method	Well-Established	High	High	High

Table 5

from the EREF report appendix and the other investigations reviewed in this ARF study.

All of the methods, except the VRPM, can be considered to have well-established implementation procedures. Because of the assumptions about local atmospheric dispersion of emissions that must be made in order to calculate the area contributing to the measured emission flux, the VRPM method is not quite as well established.

The tracer gas correlation and DIAL methods are considered to provide the most accurate measurement of landfill methane emissions because the methods directly measure mass emission rates. Based on the high levels of uncertainty reported in the EPA Field Test Program and the fact that it is a surface factor method, the accuracy of the VRPM method is reported to be in the low to medium range. The accuracy of the flux chamber and micrometeorological methods is generally concluded to be low, as both involve point-source measurements that cannot be accurately extrapolated to the entire landfill surface.

The degree of complexity in utilizing these field methods ranges from low for the flux chamber method to high for the DIAL method, with the latter requiring highly educated and trained specialists.

The degree of complexity ratings are generally mirrored in the personnel and equipment requirements. The VRPM method is also given a high (less favorable) score because of the need to transport and place large scissor-jack platforms and tunable diode lasers to perform the needed measurements.

Landfill managers increasingly must be able to determine the quantity of methane emitted by their sites. The methods reviewed in this article provide a range of options that can use local, field-measured data to develop methane emission estimates.

A companion article about the field measure of methane oxidation rates from landfill cover soils will appear in next month's issue of *MSW Management*.

Jeremy K. O'Brien, P.E., is the director of SWANA's Applied Research Foundation.

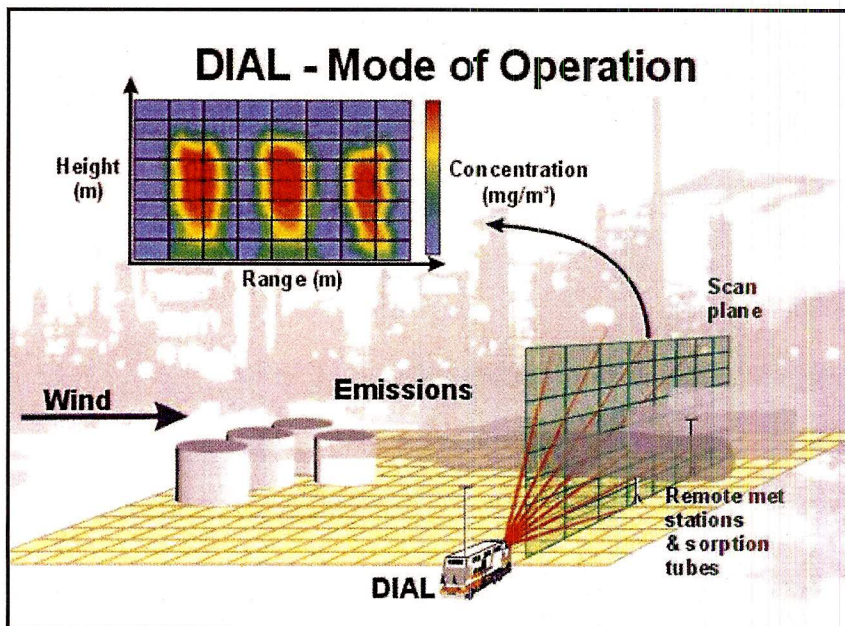


Figure 7