MEASURING LANDFILL GAS COLLECTION EFFICIENCY USING SURFACE METHANE CONCENTRATIONS

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ABSTRACT

Measuring landfill gas collection efficiency is important for gauging emission control effectiveness and energy recovery opportunities. Though researched for years, practical measures of collection efficiency are lacking. Instead, a default efficiency of 75% based on surveys of industry estimates is commonly used, for example, by the United States Environmental Protection Agency (US EPA). Though few, actual emission measurements indicate substantially higher efficiencies ranging from 85 to 98%.

The scarcity of collection efficiency measurements is due to their difficulty and cost. The Los Angeles County Sanitation Districts (Districts) developed a measure of collection efficiency using readily acquired surface methane concentrations and the US EPA's Industrial Source Complex (ISC) model. This methodology was recently applied to estimate landfill gas collection efficiency at a Districts landfill and indicates an efficiency approaching 95% or greater.

ISC model setup and application are described as well as model assumptions and their validity. Uncertainties in the model parameters and their effect on the collection efficiency calculation are presented. The significance and implications of this study are discussed.

INTRODUCTION

Methane and carbon dioxide are the end products of solid waste biodegradation under anaerobic conditions and are the primary constituents of landfill gas. Landfill gas may be recovered for a variety of purposes including subsurface migration prevention, odor and emission control, and energy recovery. Additionally national and regional jurisdictions may require landfill gas recovery, for example, the US EPA, which adopted a Municipal Solid Waste Landfill New Source Performance Standards (NSPS) in 1996.

Gas collection efficiency is important for a variety of environmental, regulatory, and engineering purposes and accordingly may be defined differently. Efficiency as used here specifically refers to the ratio of collected to generated gas during the period of collection using a well-operated gas recovery system that fully extends throughout the landfill.

A well-operated gas collection system extracts landfill gas from a system of collectors and header lines by applying a vacuum. The Districts have extensively modeled the performance of gas collectors, both vertical wells and horizontal trenches of the type used across the nation. The modeling was based on fundamental principles and used numerical methods. Landfill and cover permeability values specified in the model were calibrated so that modeled vacuums, flows and gas quality matched actual well and trench performance data. These models consistently show that the landfill gas collection efficiencies should routinely reach 100%.

Though complete gas collection may be theoretically feasible, local variations in landfill properties and gas system performance may allow some emissions. The collection efficiency achieved by actual systems has been widely debated.

According to US EPA's "Compilation of air pollution emission factors, Report AP-42", (USEPA, 1997), researchers and practitioners estimated collection efficiencies to typically range from 60 to 85%. The most commonly assumed efficiency was 75% though higher efficiencies were used at some sites, particularly those engineered to control emissions.

The US EPA continues to assume 75% default landfill gas collection efficiency based on a memorandum dated October 24, 2002 (Leatherwood, 2002). Most of the published sources cited by the memorandum are from ten years or more in the past. Consequently these sources do not reflect landfill gas system operational experience after implementation of US EPA's NSPS landfill gas control rule when it is expected that higher efficiencies became necessary for rule compliance. Most of the memorandum collection efficiency estimates were based on speculation. The only collection efficiency measurements were attributed to Dr. Stan Zison of Pacific Energy. He measured collection efficiency at three landfills operated for energy recovery purposes at 85, 90, and 95%. It is reasonable to expect that gas collection efficiency is yet higher at NSPS regulated facilities.

Spokas, et al (2005) conducted intensive field measurements at three French landfills with the aim of quantifying all of the pathways for methane generated at the sites. The collection efficiency was calculated as the ratio of recovered gas to empirically modeled gas generation.[1] Efficiencies between 88 and 98% were calculated for sites with completed clay covers similar to those widely used in North America.[2] Interestingly, the study reported direct measurements of collection and emissions, the sum of which, in the absence of any storage changes, is the generation.[3] Recalculating collection efficiency by substituting the sum of collection and emission for modeled generation indicates that the final clay covers performed uniformly well (Montreuil-sur-Barse – 93%; Lapouyade – 93% (summer) and 99% (winter); and Grand'landes – 100%). This supports the study's original findings of high collection efficiency and suggests that the actual values may be higher yet.

As gas generation cannot be modeled with any certainty for a particular landfill, emission and collection measurements can be summed to provide an estimate of generation. While collection measurement is straightforward, several approaches have been proposed or used for emission measurements. Tregourès, et al (1999) compared several direct and indirect emission measurement methods (i.e., thermography, flux chambers, tracers, eddy correlation, and mass balance) at a 20 acre uncontrolled landfill.

Each of the evaluated methods had disadvantages. The eddy correlation method was found to be unsuitable due to the spatial variability of emissions. The thermography and mass balance methods were yet in development. Tracer gas methods require comprehensive plume coverage that can be problematic.[4] Flux chambers are in principle effective but due to emission spatial variability and the chambers' small size require hundreds of measurements (or in the case of large sites such as those operated by the Districts several hundreds or thousands of measurements).

A recurring problem for these methods was the spatial variability of the emissions. An empirical method for spatially characterizing landfill emissions was developed over twenty-five years ago by the Districts and involves measuring the surface methane concentrations across the landfill. As originally implemented, an air sample was continuously composited into a Tedlar® bag from a probe swept across the landfill surface along a predefined route. The routes were spaced to provide uniform coverage. The bag samples were analyzed for methane by flame ionization detector (FID). This provided a measure of the "integrated surface methane" (ISM) level along each route.

The South Coast Air Quality Management District (SCAQMD) adapted the Districts ISM method for their Rule 1150.1 regulating landfills in preference to other methods such as flux chambers. SCAQMD set a 50-ppm methane limit for the ISM samples to ensure effective emission control. Rule 1150.1 standardized the integrated monitoring by dividing the landfill into 50,000 square foot grids and requiring an approximately 2,600 foot long uniformly spaced route be monitored within each grid.[5] Bag samples are no longer routinely used. Instead portable FID units equipped with data loggers record readings every four seconds. The data logger values are then averaged for each grid.

Huitric (1996, 2004) developed a methodology to estimate collection efficiency at a landfill using ISM data and the reduction in ISM due to landfill gas collection as modeled by US EPA's Industrial Source Complex (ISC) atmospheric dispersion modeling methods. The basis for this calculation is theory, used by ISC, showing that the surface methane concentration from an area source such as a landfill is directly proportional to its emission rate. The ISC model corrects for meteorological variables that affect this proportionality.

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[1] Using modeled gas generation introduces uncertainty. For example, US EPA (1997) found that their model calibrated from 21 landfills projected flows ranging from 38 to 492% of actual levels.

[2] Other monitored cover materials include thin temporary clay, geomembrane, and GCL. Except for the GCL, these also performed well with collection efficiency ranging from 84 to 93%. The GCL had a 41% collection efficiency.

[3] Spokas, et al (2005) indicate that there may have been changes in landfill gas storage. However if storage proportionately affects collection and emission, as seems likely, collection efficiency calculated from these values would still be correct. Regardless, any effects from storage would tend to average out among the sites.

[4] Plume coverage becomes more difficult at larger sites such as those operated by the Districts. An added plume coverage problem for Districts landfills and others situated in coastal areas is the continuously shifting wind directions responding to the diurnal land and sea breeze patterns.

[5] SCAQMD also adapted a simpler protocol whereby instantaneous methane emissions were directly measured by monitoring the landfill surface with a portable FID. SCAQMD set a 500 ppm limit for the instantaneous method. Though developed by SCAQMD as a check for cover integrity, a grid's peak instantaneous level is roughly correlated with its integrated level ($r^2 \sim 0.5$ for log transformed values). The instantaneous method was later adapted by the US EPA for their landfill NSPS.

FIGURE 1. Palos Verdes Landfill.

Using ISM data and ISC modeling, the collection efficiency can be expressed as the ratio of surface methane concentration reduction achieved by landfill gas collection to the total potential surface methane concentration due to generation. The latter is represented by the sum of the measured ISM and the modeled surface methane reduction due to landfill gas collection.

An onsite meteorology station required by SCAQMD for Rule 1150.1 provides the wind speed and direction data needed for the ISC model. Meteorology data preprocessing is necessary for ISC use. US EPA and others provide tools or services to perform the preprocessing.

The methodology discussed in this paper couples surface methane measurements (ISM) that capture the spatial variability of actual emissions with atmospheric dispersion modeling (ISC). This approach provides a more cost effective alternative to estimate gas collection efficiency than other methods considered.

BACKGROUND

The Districts are a confederation of 25 independent special districts serving the water pollution control and solid waste management needs of more than five million people in Los Angeles County. The Districts manage a comprehensive solid waste management system including three active sanitary landfills that receive approximately 16,000 tons of trash per day (about half of the County-wide disposal capacity), three closed landfills, three material recovery/transfer facilities, three landfill gas-to-energy facilities, two recycle centers, a refuse-to-energy facility, and participate in the operation of a second refuse-to-energy facility.

Over 30 years ago, the Districts pioneered the use of comprehensive landfill gas management systems. These were comprised of collectors (vertical wells and horizontal trenches), headerlines, blowers, and flares. The Districts' first full-scale gas collection system was constructed at their Palos Verdes Landfill (PVLF) in 1971 initially for migration control purposes and later for emission control and energy recovery. The Districts developed an innovative methodology for estimating gas collection efficiency utilizing surface methane concentration data. That methodology was applied at PVLF to help assess that site's gas system performance as described in the following sections.

SITE INFORMATION

PVLF is a 291 acre closed landfill located in the City of Rolling Hills Estates on the Palos Verdes Peninsula at the southwest portion of Los Angeles County. The Districts acquired PVLF in 1957 and proceeded to operate it as a municipal solid waste (MSW) disposal site with minor amounts of industrial and hazardous waste, 3 to 4% of the total. PVLF ceased waste disposal in 1980 after receiving 23.6 million tons.

PVLF was partially developed and now has three distinct areas, the South Coast Botanic Garden (SCBG) - 83 acres, Ernie Howlett Park - 35 acres, and the Main Site - 173 acres (see Figure 1). SCBG was developed over the oldest portion of the landfill and is now owned and operated by the Los Angeles County Department of Parks and Recreation. SCBG was opened prior to the development of landfill gas collection systems and, today, is equipped with a perimeter migration control system and a limited interior system. A more extensive gas collection system has not been necessary as monitoring shows that emissions are low and in compliance with SCAQMD requirements. SCBG was not included in this evaluation.

The Ernie Howlett Park is owned and operated by the City of Rolling Hills Estates. When filled, it excluded industrial, commercial and residential waste but instead received materials consisting largely of inerts such as demolition waste with little or no low organic content. This site produces little gas and has not been required to install a landfill gas collection system and is not part of this evaluation.

The Main Site was operated as an MSW site with minor industrial and hazardous waste disposal. After closure in 1980, it was provided with a five-foot thick clay cover. PVLF is fully equipped with a gas collection system regulated by SCAQMD's Rule 1150.1. The collection efficiency for the Main Site was investigated for environmental assessment purposes.

SURFACE EMISSIONS MONITORING

As described in the Introduction, the Districts developed an "integrated surface methane" (ISM) methodology in the 1980's as a practical measure of emissions. There are about equal amounts of methane and carbon dioxide in landfill gas but only the methane is monitored as it is easily measured, and importantly, far more readily distinguished from the ambient air background (<2 ppm) than carbon dioxide is from its background (360 ppm). As methane is proportionate to other landfill gas constituents, it can be used as a surrogate for landfill gas.

The Districts presently use at PVLF a SEM-500 FID monitor to measure landfill surface methane. This unit has a built-in data logger and is specifically made for ISM monitoring.

SCAQMD adopted ISM monitoring in 1985 as one of its Rule 1150.1 requirements, (SCAQMD, 1985). Rule 1150.1 specifies that a landfill be divided into 50,000 square foot grids. PVLF Main Site was divided into 137 grids as shown on Figure 2. Rule 1150.1 further specifies that each grid be monitored along a sinuous uniformly space 2,600 foot long route. SCAQMD limits the average methane to 50 ppm on each route when measured within three inches of the landfill surface. Figure 3 illustrates an example grid with a 2,600 foot long ISM route.

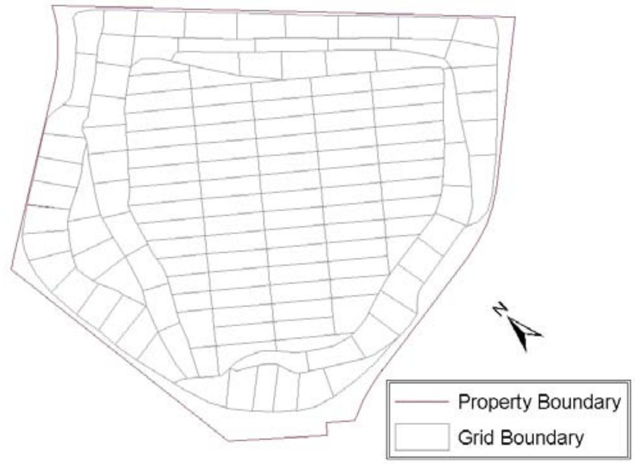

FIGURE 2. Palos Verdes Landfill Main Site ISM grid monitoring layout.

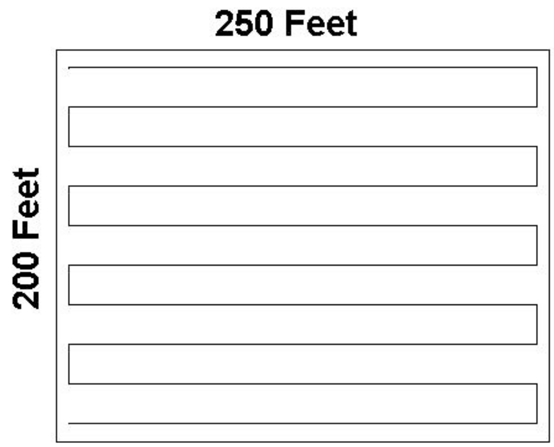

FIGURE 3. Grid schematic with 2,600 foot ISM route.

The consecutive loops in the route shown in Figure 3 are about 20 feet apart. The FID data logger system records measurements every four seconds so that readings are obtained at approximately seven foot intervals. This provides about one reading for every 140 square feet. In all, more than 50,000 readings for the Main Site are obtained over the 137 grids.

The SCAQMD specifies that monitoring be done at wind speeds below five miles per hour (mph). Because wind speeds pick up in the late morning or early afternoon, monitoring generally starts early each day and terminates around noon. A technician can monitor the Main Site over twelve days. The actual time may be longer as Rule 1150.1 prohibits monitoring during storms and for 72 hours afterwards so as to avoid turbulent atmospheric conditions.

Because a data logger is used to record the ISM monitoring results at four-second intervals, very precise information can be developed relative to the data distribution. Table 1 presents five ranges of ISM levels and their corresponding average methane concentration, average concentration corrected for bias[6] and ambient air background[7], and percent in each range. These results represent more than 200,000 four-second readings taken over four quarterly monitoring events between July 2001 and June 2002.

TABLE 1. ISM results over four quarterly monitoring events (7/2001 – 6/2002).

ISM Methane, ppm			%Readings
Range	Average	Background Corrected	
<10	2.33	0.553	99.2319
10 - 25	14.6	12.8	0.6050
25 - 50	34.0	32.2	0.1132
50 - 100	65.8	64.0	0.0336
100 - 500	189	187	0.0163
All	2.49	0.714	100

The percent readings at various methane ranges are equivalent to the percent area of the landfill at various surface methane levels. Less than 1% of the landfill surface had levels above 10 ppm methane. The entire landfill averaged just 0.714 ppm above background. There were no exceedances of the Rule 1150.1 and NSPS 500 ppm instantaneous limit during ISM monitoring. This indicates excellent surface emission control conditions.

An often-expressed concern with respect to quantifying a landfill's mass emission rate using other methodologies (e.g., flux chambers) is that most emissions may be released from small but high emission areas that may go undetected. The ISM data logger results can be analyzed to address this concern. Since for each ISM range the emission rate is proportional to the ISM concentration, the product of the percent area and of the average concentration is proportional to the mass emission rate.[8] The distribution of emission mass relative to emission levels is shown in Figure 4. It shows that even a naïve sampling program that missed elevated emission areas would still account for 77% of total emissions. On the other hand, a sampling program focused just on the high emission areas would over estimate total emissions by more than 260 times the actual amount.[9]

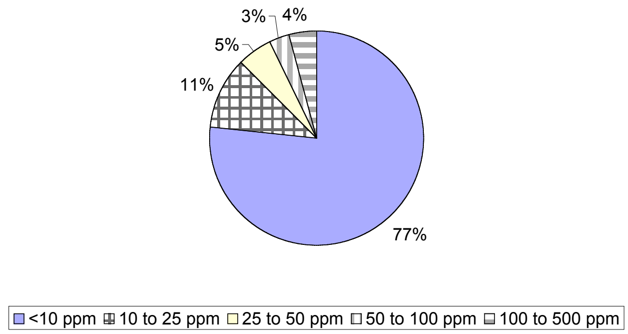

FIGURE 4. Distribution of emissions by ISM levels (7/2001 – 6/2002).

MODELING LANDFILL SURFACE GAS LEVELS

The US EPA's ISC model is one of the most used air quality models simulating air dispersion mechanisms to study air quality impacts. The ISC model is capable of estimating short term and long term gas concentration or deposition values, from multiple sources, on specific locations (i.e., receptors).

In the past, the ISC model has been applied to study the air quality impacts of landfill surface gas emissions (i.e., NYSDH, 2000, 2002; Paraskaki and Lazaridis, 2005). Previous ISC model landfill applications predicted gas concentration levels down wind under assumed emission rates. In this study, the ISC model is used to predict the landfill surface methane concentration reductions achieved by landfill gas collection. For PVLF, the Breeze/ISC model, an air quality modeling system based on US EPA's ISC source-code and developed by Trinity Consultants, is used to estimate surface methane levels at PVLF.

US EPA's ISC model demonstrates that for an area source, the emission rate and resulting emission levels are directly linear with one another. This relationship is shown by the area source dispersion Equation 1-65 within the ISC model documentation (US EPA, 1999):

$$\chi = \frac{Q_A K}{2\pi u_S} \int_X \frac{VD}{\sigma_Y \sigma_Z} \left(\int_Y \exp\left[-0.5 \left(\frac{y}{\sigma_Y} \right)^2 \right] dy \right) dx \qquad \textbf{(1)}$$

where _ is the concentration at any particular receptor location and Q_A is the area source emission rate. K is a scaling coefficient to convert calculated concentration to desired units (default value of 10^6 for Q_A in g/s and

[6] The FID unit had a slight drift from the initial calibration at the start of each monitoring session to the last reading when the calibration was rechecked. Though insignificant, this bias was corrected by adding 0.059 ppm to each reading.

[7] California ambient air background is about 1.835 ppm (Prinn, R. G. and R. F. Weiss, 2005); this value is subtracted from measured readings.

[8] Calculations are performed with ISM levels corrected for ambient air methane background and measurement bias.

[9] Calculated as the ratio of the average value above 100 ppm (187 ppm above background) to the average site wide value (0.714 ppm above background).

concentration _ in _g/m^3). V is the vertical term accounts for the vertical distribution of the Gaussian plume. D is the decay term accounting for pollutant removal by physical or chemical processes along the downwind distance x. u_s is the mean wind speed (m/s) at release height. $\_y$, $\_z$ are standard deviation of lateral and vertical concentration distribution (m). Empirical ISC modeling also shows the same linear relationship between the emission rate and the average surface level projected by the model.

COLLECTION EFFICIENCY CALCULATION

The linearity between the emission rate and the resulting surface gas level allows the usual definition of gas collection efficiency (i.e., the ratio of measured collected gases to an uncertain amount of generated gases) to be restated in terms of surface gas concentrations. Because methane is readily measured within surface gases and because it is proportionate to total gas emissions, it is used here for calculating collection efficiency.

The ISC model can be used to transform the amount of collected methane to an equivalent reduction in surface methane levels achieved by gas collection, ISM_r. Gas generation is then expressed as the sum of the modeled reduction in surface methane due to collection, ISM_r, and the measured surface methane due to emissions, ISM_e. Gas collection efficiency is then calculated by Equation 2:

$$E = \frac{ISM_r}{ISM_r + ISM_e} \quad \textbf{(2)}$$

Details of the procedures of this methodology are further discussed in the following subsections.

PVLF ISM_E Levels

PVLF is subject to the SCAQMD Rule 1150.1 landfill gas monitoring program. One component of Rule 1150.1 is to monitor the landfill's average methane levels within three inches of the fill surface on a quarterly basis. In accordance with the rule, the landfill surface is divided into 137 grids, each about 50,000 square feet in area. Each grid is evenly monitored along a sinuous half-mile path. This procedure provides an average surface methane level by continuous sampling along the route. This is similar to the US EPA's landfill NSPS monitoring methodology that is used to obtain peak surface methane levels.

Monitoring is performed with a continuously sampling device (SEM-500) using a probe swept across the grid within three inches of its surface. The SEM-500 is specifically made for monitoring landfill surface emissions and is equipped with an FID detector calibrated to methane. The instrument is calibrated before each daily monitoring session. A range of calibration gases is used including: hydrocarbon free air (< 0.1 ppm HC as CH_4), a level near that typically measured at the landfill (3.05 ppm CH4), a level near the Rule 1150.1 50 ppm integrated (i.e., average grid) limit (52.40 ppm CH_4), and a level near the Rule 1150.1 500 ppm instantaneous (i.e., point) limit (500.70 ppm CH4).

The SEM-500 is retested against the calibration gases at the beginning and end of each daily monitoring. Examination of results for the calibration gas closest to the actual field levels (i.e., 3.05 ppm CH_4) shows a slight instrument bias. Overall instrument readings were just 0.059 ppm less than the 3.05 ppm CH_4 calibration gas. The collection efficiency calculation is corrected for this difference. The effect on the collection efficiency calculation is negligible (much less than 1%).

The SCAQMD Rule 1150.1 limits monitoring to periods with wind speeds of less than five mph. These conditions occur primarily in the morning hours. Monitoring is typically conducted for about five hours each session before winds become excessive.

The raw ISM monitoring data are stored in an MS Access database indexed by grid number and time of monitoring. This database contains four-second readings for each grid monitored on four separate quarterly monitoring events between July 2001 and June 2002. Coordinates for grid centroids were entered as well as the centroids' relative positions determined as a percentage of the landfills width and length. These latter values allowed the grid results to be mapped to the ISC model results that were obtained for a square receptor area approximating the landfill footprint.

A statistical analysis was performed to gauge the uncertainty in the average surface methane monitoring results. As some samples correspond to calm periods when the ISC model produces no results, these were removed from the data set. There remained 528 of the original 548 grid readings. A Bootstrap analysis (N=2000) was performed to determine a 95% confidence interval about the mean value. The Bootstrap average, 2.490 ppm as CH_4, was essentially identical to the dataset average (2.490 ppm). The Bootstrap bias was well less than 1 ppb. The Bootstrap standard deviation was 0.04412 ppm. The 95% confidence interval was calculated to be 2.490 ± 0.086 ppm. These results indicate that the surface methane concentrations were measured to a high degree of accuracy.

PVLF Methane Collection

The ISC model is used to estimate the landfill surface methane concentration reduction due to gas recovery. The landfill gas flow and quality are continuously recorded at PVLF's energy recovery plant. The average methane recovery from the Main Site at PVLF between July 2001 and June 2002 was 894 scfm over 163.9 acres or, equivalently, 0.00042 g/s-m^2 in units required by the ISC model.

Meteorology Data

The meteorological data were from the onsite Climatronics Model F460 weather station. This unit has a threshold wind speed sensitivity of 0.22 m/s and an accuracy of 0.07 m/s or 1% (whichever is greater). The wind direction is accurate to 2 degrees. The Climatronics unit provides 15-minute observations of temperature, wind direction, wind speed, and sigma-theta (standard deviation of the horizontal wind direction). The data were preprocessed for the ISC model, per US EPA guidelines by Trinity Consultants using US EPA's program Meteorological Preprocessor for Regulatory Modeling (MPRM).

Preprocessing identifies calms that cannot be modeled. It also increases as necessary wind speeds to a minimum of 1 meter per second (mps) for non-calm periods. Finally, the preprocessor determines a stability category ("A" through "F") for each hour. The stability classes were computed using the sigma-theta observations. As for mixing heights, Miramar and Oakland are the only two full-time stations in California. As the Miramar station is much closer, it was used for mixing heights.

The ISC model ignores hours with calm conditions as receptor concentrations cannot be calculated for these. Less than 4% of grids (i.e., 20 of 548) were monitored during calms. The modeled receptor levels for calm periods are flagged as "0" to show that these should be ignored.

The ISC model can create exceedingly large output files for hourly meteorologic data over a year's time. To make the ISC output file more manageable, the preprocessed file was filtered to retain only hours corresponding to times of ISM monitoring. The filtered preprocessed meteorologic file was assigned an arbitrary time stamp of consecutive hours that was later related within a database to the true time. Changing the hours after preprocessing does not affect the ISC model output other than to reduce its size.

ISC Model Application

The ISC model was used in the standard regulatory default mode. The model requires that the area source be defined as well as receptor locations. The PVLF Main Site is approximately represented as a square source area 810 meters on a side. Because surface methane level reduction due to collection is sought, the source area also serves as the receptor. The receptor area was uniformly divided into 256 square grids with 289 nodal points, that is, 17 nodes by 17 nodes. The receptors are set at an elevation of 0.0381 meters (1.5 inches), which represents half the three-inch height limit from the ground surface specified by Rule 1150.1.

A source emission rate is specified in the ISC model corresponding to the landfill methane collection rate as described above. The ISC model was used in both the Urban and Rural modes. These modes adjust for the relative amounts of dispersion associated with urban or rural settings. US EPA guidance indicates that due to the surrounding population density, the Urban mode should be used. However as the landfill itself is similar to a rural setting, the Rural mode was also modeled.

The ISC model "day table" setting was used to specify hourly model output for each node. A simple program was written to extract the modeled emission level for each receptor node at each modeled hour. The results were placed into a database for analysis. This format allows the specific output for each receptor node and each hour to be related to the actual grid ISM measurements. These two sets of values are used together to calculate gas collection efficiency using Equation 2 for each grid measurement.

LANDFILL COVER OXIDATION EFFECTS

To this point, it has been assumed that methane is a conservative tracer of landfill gas emissions. However there is extensive literature documenting that landfill cover soils can develop a high capacity for methane oxidation by methanotrophic bacteria. Additionally, landfill cover soils have a significant potential for cometabolic degradation of trace gases, thereby reducing overall gas emissions (Scheutz, et al., 2004). This section addresses landfill cover oxidation effects on the calculated landfill gas collection efficiency.

As previously noted, the definition of collection efficiency may depend on its particular application. In the context of green house gas issues, it does not matter in a practical sense whether methane is recovered or oxidized within the landfill cover. What is important is the overall reduction in methane emission. The approach proposed here for calculating collection efficiency appropriately reflects the overall methane removal. For energy recovery purposes, the amount of methane lost to cover oxidation is likely unrecoverable for practical uses. Again the proposed approach to calculating collection efficiency appears appropriate.

Trace landfill gas constituents include halogenated and aromatic hydrocarbons and sulfur- and oxygen-containing compounds. Several important trace gases are oxidized within landfill covers. From a public health risk perspective, the most important trace gas constituents are generally vinyl chloride and benzene due to their potency and concentration. Both of these are oxidized in landfill covers. Scheutz, et al. (2004) performed a well-controlled experiment on methane and trace gas oxidation in landfill soils and reported the kinetic rates under ideal conditions. The laboratory findings were applied to a simple model of a landfill gas-air mixture in a landfill cover soil with 33% porosity. The results are shown in Figure 5 and indicate that less than half of the methane would be oxidized while most of the vinyl chloride and benzene would be oxidized after 0.2 hours. Under non-ideal field conditions (e.g., moisture above or below optimum), the actual oxidation rates could decline considerably. However the relative oxidation rates should approximately hold. Again the proposed reliance on surface methane measurements and ISC modeling for calculating collection efficiency appears to be conservative with respect to health risk issues.

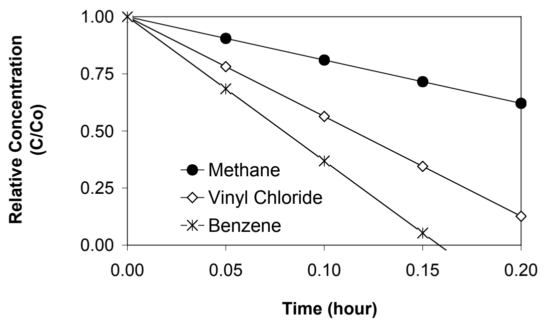

FIGURE 5. Relative oxidation rates for selected landfill gas constituents in soil.

COLLECTION EFFICIENCY RESULTS

The results of a detailed grid-by-grid analysis of collection efficiency as described in the preceding sections are reported below. Additionally, two simpler methods, an averaged grid emission analysis and a weighted average analysis are reported below for comparison purposes.

Grid-By-Grid Analysis

Twenty of the 548 grid samplings occurred during calms. As ISC ignores calms, 528 ISM grid samplings were analyzed. The ISC modeled the reduction in surface methane levels (i.e., ISM_r) due to gas collection to be on average 9.807 and 18.856 ppm methane for the Urban and Rural modes, respectively. Figure 6 shows the average ISM_r (in _G/m3) for the Rural mode.

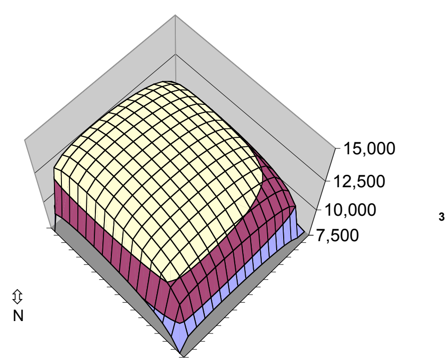

FIGURE 6. Average ISC modeled ISM_r for rural mode.

The four second SEM-500 readings were averaged for each grid for each quarterly monitoring. The average of all grid readings was 2.490 ppm. Correcting for ambient air background and a slight instrument bias provides an average emission level (ISM_e) of 0.714 ppm. The total potential surface emission level due to generation in the absence of collection was represented as the sum of ISM_r and ISM_e, 10.521 and 19.570 ppm for the Urban and Rural modes, respectively.

The collection efficiency for PVLF was calculated by Equation 2 (i.e., $E = ISM_r/(ISM_r + ISM_e)$) on a grid by grid basis for each quarterly monitoring. The averaged ISM_e and modeled ISM_r values were related to one another by a coordinate system that adjusted for the differences between the actual landfill footprint and the modeled square receptor area specified for ISC. The collection efficiency was calculated for all 137 PVLF grids for each quarterly monitoring excluding calms.

The grid-by-grid average and 95% confidence intervals for the 528 grid collection efficiency measurements are shown in Table 2. These results are consistent with those for the three French landfills (Spokas, *et al.*, 2005) showing high collection efficiency.

TABLE 2. Grid-by-grid collection efficiency.

	ISC Mode	
Collection Efficiency	**Urban**	**Rural**
Lower Bound	92.9%	95.9%
Average	93.8%	96.5%
Upper Bound	94.5%	97.1%

Averaged Grid Emission Analysis

Inspection of the emission reduction, ISM_r, modeled by ISC shows that these are nearly uniform except near the landfill boundaries (see Figure 6). As such, it is reasonable to expect that a simpler approach based on the overall average emissions, ISM_e, and average modeled emissions reduction, ISM_r, would be nearly as effective as the grid-by-grid analysis. Table 3 presents the results of an averaged approach. The averaging approach compares well with the more detailed grid-by-grid approach (i.e.,Table 2.)

TABLE 3. Averaged grid emission analysis.

	ISC Mode	
Methane, ppm	**Urban**	**Rural**
Measured LF Surface[a]	2.4	2.49
Bias Correction	+0.0	+0.05
Actual LF Surface	2.5	2.54
Air Background[b]	-1.8	-1.83
LF Emission (ISM_e)	0.7	0.71
Emissions Reduction (ISM_r)	+9.8	+18.856
Total Emissions Potential ($ISM_r + ISM_e$)	10.5	19.57
Collection Efficiency	**93.2%**	**96.4%**

[a] Excludes calms not modeled by ISC.

[b.] Prinn, R. G. and R. F. Weiss (2005).

Figure 7 illustrates the average measured emission levels relative to the average modeled emissions reduction as summarized in Table 3. This graph shows the uncertainty in the ISC model with respect to the Urban and Rural modes. As the actual emissions (0.714 ppm ISM_e) at PVLF are low, the calculated collection efficiency does not greatly differ between the two modes. However a site with the same emissions reduction, ISM_r, but with a much greater actual emission levels, say 5 ppm ISM_e, would have calculated collection efficiency values of roughly 67% and 80% for Urban and Rural modes, respectively. This indicates that this methodology performs best with high efficiency collection systems but may be less precise for lower efficiency systems, particularly where there may be some question as to the precise mode (Urban or Rural) that should be used.

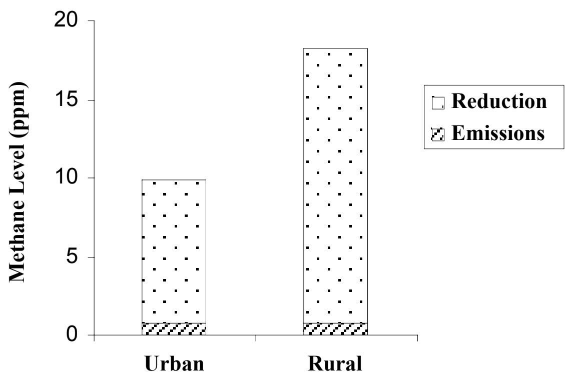

FIGURE 7. Diagram showing averages for measured emissions (ISM_e) and modeled emissions reduction (ISM_r) from Table 3.

Weighted Average Analysis

One final approach was taken to analyzing collection efficiency using ISC modeling and ISM monitoring. The goal for this approach was to drastically reduce the ISC output file to a more manageable size.

As a first step, a frequency analysis of the preprocessed meteorology data file was made for hours corresponding to ISM monitoring. The preprocessed file contains, with two exceptions, the original wind speeds in meters per second (mps) and an assigned stability category ("A" through "F"). Hours with calms have an assigned wind speed of 0 mps and are unused by ISC. Under certain conditions, the preprocessor will increase the wind speed to a minimum of 1 mps.

The frequency analysis was created using ten wind speed ranges and six stability categories ("A" through "F"). The first wind speed was exactly 1 mps to accommodate those values raised to that minimum level by preprocessing. The remaining wind speeds were grouped into ranges occurring in 0.25 mps increments starting at 1 to 1.25 mps, 1.25 to 1.5 mps, and so forth. Only 32 of the possible 60 combinations of wind speed and stability categories occurred. Excluding calms, the percent frequency for each combination was determined.

An ISC meteorological file was created reflecting the 32 wind speed and stability combinations. For ranges of wind speeds (i.e., 1 to 1.25, 1.25 to 1.5, etc.) the wind speed range average was used (i.e., 1.125, 1.375, etc.). All other ISC settings were kept the same as previously used. This approach reduced the output file by 94%.

The weighted average methane reduction due to collection, ISM_r, was calculated from the model output and frequency for each wind speed and stability combination. These results are summarized on Table 4 and are nearly identical to those shown on Table 3. Procedurally this method was far simpler than either of the other two presented above due to the greatly reduced ISC output file size.

TABLE 4. Weighted average collection efficiency.

	ISC Mode	
Methane, ppm	**Urban**	**Rural**
Measured LF Surface[a]	2.4	2.49
Bias Correction	+0.0	+0.05
Actual LF Surface	2.5	2.54
Air Background[b]	-1.8	-1.83
LF Emission (ISM_e)	0.7	0.71
Emissions Reduction (ISM_r)	+9.2	+17.740
Total Emissions Potential (ISM_r + ISM_e)	9.9	18.45
Collection Efficiency	**92.8%**	**96.1%**

[a] Excludes calms not modeled by ISC.
[b.] Prinn, R. G. and R. F. Weiss (2005)

DISCUSSION

As presented in Table 2, a grid-by-grid analysis shows that the PVLF gas collection efficiency approaches or exceeds 95% (93.8% for Urban mode, and 96.5% for Rural). These findings are in good agreement with the few collection efficiency field measurements reported by others (e.g., Dr. Stan Zison as reported by Leatherwood, C., 2002, and Spokas, K. et al., 2005). It appears that widely used default collection efficiency values such as 75% may grossly underestimate the true collection efficiency, particularly for landfills operated for emission control purposes (e.g., US EPA Municipal Solid Waste NSPS and SCAQMD Rule 1150.1).

As shown in Tables 3 and 4, simplified collection efficiency calculations perform nearly as well as the detailed grid-by-grid analysis performed for Table 2. This indicates that the results are likely not sensitive to simplifying assumptions made here with respect to the exact landfill footprint modeled with ISC, namely using square source and receptor areas in lieu of more precisely defined areas as allowed by ISC.

There may be many landfills where this methodology may be practical. The weighted average approach used for Table 4 greatly simplifies implementation of this method from a modeling and analysis standpoint. For landfills regulated by NSPS, the data logger equipped portable FID unit used for methane monitoring may already be available.

Rule 1150.1 used at PVLF requires five times more surface monitoring than NSPS (i.e., route placement about every 20 feet for Rule 1150.1 versus about 100 feet for NSPS). Some consideration should be given as to whether this lowered intensity may adversely affect the precision of the ISM_e value.

Precision may become a significant issue at landfills with low emission rates due to small size or large age. At some point, such sites will become impractical to monitor since the surface methane level will be too slight to detect above the ambient background. Similarly, landfills situated in regions with wind speeds higher than at PVLF may find that the surface methane levels are too dilute to reliably measure.

A representative weather data set is needed for the ISC model concurrent with ISM_e monitoring. An onsite weather station is ideal but many landfills may be situated near existing weather stations that adequately represent landfill conditions. Weather data preprocessing requires mixing height data that may be available only from remote regional monitoring stations. Expert assistance may be needed to obtain such data and complete data preprocessing for ISC.

CONCLUDING REMARKS

A new methodology for estimating a landfill gas system's collection efficiency has been presented and discussed in this paper. Unlike other methods used in estimating collection efficiency, such as flux chamber and tracer gas methods, this methodology combines the applications of surface methane concentration measurements with air dispersion modeling in an innovative manner to provide comprehensive spatial coverage with a minimum of difficulty. As an alternative to other viable methods, we believe this methodology provides a useful, time-efficient and cost-effective, and practical tool to estimate a landfill gas system's collection efficiency. To demonstrate the usefulness of this methodology, it has been applied to estimate landfill gas collection efficiency at the Districts' Palos Verdes Landfill with results indicating an efficiency approaching 95% or more.

As discussed in previous sections, we believe that the commonly assumed default collection efficiency value of 75% is dated and does not reflect modern conditions for NSPS regulated landfills and other landfills operated for emission control purposes.

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