FIELD COMPARISON OF LANDFILL GAS COLLECTION EFFICIENCY MEASUREMENTS

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ABSTRACT

Gas collection efficiency is important for a variety of environmental, regulatory, and engineering purposes in landfill management. However collection efficiency measurements are typically complex and costly and so are seldom made. Instead conservative collection efficiencies are typically assumed, for example, 75% by the US Environmental Protection Agency (US EPA).

In the 1990's, the Los Angeles County Sanitation Districts (Districts) developed an innovative methodology for measuring gas collection efficiency based on a combination of readily acquired integrated surface methane (ISM) concentration data and modeling using the US EPA's Industrial Source Complex (ISC) air dispersion model. The Districts previously reported application of this "ISM/ISC" method to their Palos Verdes Landfill using four quarterly ISM monitoring events for fiscal year 2001/2002. The landfill gas collection system at this site is operated for energy recovery and emission control purposes. A collection efficiency of about 95% was measured.

This paper presents a recent Districts study comparing the ISM/ISC method with conventional static flux chamber emission measurements at the Palos Verdes Landfill. ISM prescreening was used in Spring 2006 to identify ten flux chamber measurement locations chosen to represent both peak and typical emission areas. The flux chambers were monitored in Summer 2006 for methane at five-minute intervals over 35 minutes. Additionally, chamber samples taken at the start and end of each test were analyzed for toxic constituents by US EPA Method TO-15 using single ion monitoring (SIM) technology for low detection limits.

The ISM/ISC method showed +99.2% collection efficiency for the 2006 data set. The increase in efficiency from that measured for the 2001/2002 data set corresponds to improvements in the gas collection system in the intervening time. The flux chambers found no statistically significant methane accumulation. The flux chamber methane levels were not significantly different from the global background for California. The initial and final EPA TO-15 SIM constituent concentrations were not significantly different from one another. Collection efficiencies based on flux chamber measurements were calculated to be essentially 100%. The ISM/ISC results were consistent with those from costlier flux chamber measurements. Methane used by the ISM/ISC method served as a conservative surrogate for EPA TO-15 SIM constituents measured by the flux chambers.

The ISM/ISC and flux chamber methods measured collection efficiencies above 99%. These results indicate that commonly assumed collection efficiencies of 75% can be grossly conservative for landfills operated for emission control purposes.

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 1996 US EPA Municipal Solid Waste Landfill New Source Performance Standards (NSPS) require landfill gas recovery for air quality purposes.

Gas collection efficiency may be defined differently for various environmental, regulatory, and engineering purposes. 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.

This work is a continuation of a previous study on landfill gas systems' collection efficiency estimations. In previous work (Huitric and Kong, 2006), an innovative methodology was reported that combines routine "integrated surface methane" (ISM) measurements with US EPA's Industrial Source Complex (ISC) air dispersion model to estimate collection efficiency. This approach has two advantages over other methods. It provides comprehensive and uniform spatial coverage and it is based on relatively simple field monitoring techniques.

In this study, the ISM/ISC method is compared with conventional static surface flux chamber measurements. Surface flux chamber testing quantifies actual emission rates at specific locations on the landfill cover. Though periodically used for this purpose, flux chamber testing has the disadvantage of providing poor spatial coverage. This shortcoming was addressed in this study by prescreening the landfill surface using concurrent ISM and volatile organic compound (ISV) monitoring using a portable meter equipped with a flame ionization detector (FID) and photo-ionization detector (PID). Flux chamber locations were then selected to represent the peak and typical emission areas as indicated by the ISM and ISV results. The overall objectives of this study are to compare flux chamber and ISM/ISC results and to develop optimal emission estimates for purposes of calculating collection efficiency at Palos Verdes landfill (PVLF).

FIGURE 1. Palos Verdes Landfill.

BACKGROUND

A well-operated gas collection system extracts landfill gas from a system of collectors and header lines by applying a constant 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% for a well operated system that has full coverage within the refuse.

In a recent study (Huitric and Kong, 2006), landfill gas collection efficiency was estimated employing a methodology that combines routine surface methane monitoring (ISM) with atmospheric dispersion modeling (ISC). This ISM/ISC approach yielded collection efficiencies of 94% ~ 96% at PVLF for fiscal year 2001-2002. These high collection efficiencies are in accordance with collection efficiency values derived from actual field measurements reported by other researchers (e.g., Spokas, et al., 2006). These collection efficiencies are much higher than the 75% default value assumed by the US EPA in its *Compilation of Air Pollutant Emission Factors* (AP-42) document. US EPA's default value was based on a memorandum (Leatherwood, 2002) citing information dating ten years or more before implementation of the

NSPS landfill gas control regulations. As higher efficiencies are necessary for NSPS compliance, it is reasonable to expect that gas collection efficiencies are now much higher than the 75% default value at NSPS regulated landfills.

Collection efficiencies are directly related to LFG collection and surface emission rates as described later. While collection measurements are straightforward, several approaches have been proposed or used for emission measurements. Trègourés, et al. (1999) compared several direct and indirect emission measurement methods (e.g., thermography, flux chambers, tracers, eddy correlation, and mass balance) at a 20-acre uncontrolled landfill. One effective method to quantify LFG surface emission rates is the use of surface flux chambers. This closed-chamber direct surface emission measurement approach has been used in quantifying actual emission rates of methane and other volatile organic compounds (VOCs) from area sources (such as landfill surfaces) in earlier studies (e.g., Bogner, et al., 1995, 1997, Schmidt, et al., 1998, Chan and Parkin, 2001). The US EPA has developed guidelines for applications of this technology to land surfaces (US EPA, 1986). This technology has been proven to be relatively easy-to-use, straightforward, and can provide accurate and reliable emission assessments. However, application of flux chambers to landfills has been problematic owing to high emission spatial variability so that a very large number of measurements may be needed even at small landfills. At PVLF, typical and peak emission areas were targeted using ISM and ISV prescreening measurements to address variability.

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 accepting 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) with 83 acres, Ernie Howlett Park with 35 acres, and the Main Site with 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 local 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 does not require a landfill gas collection system and was 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 clay cover averaging over seven feet in thickness. PVLF is fully equipped with a gas collection system regulated by the South Coast Air Quality Management District's (SCAQMD) landfill gas control rule, Rule 1150.1. Rule 1150.1 is similar to but more rigorous than US EPA's NSPS landfill emission control rule. As the Main Site received limited amounts of hazardous waste, it also falls under the jurisdiction of the California Department of Toxic Substance Control (DTSC). The collection efficiency for the Main Site was investigated using results from a DTSC required emission test program.

ISM/ISC TECHNICAL APPROACH

This study combines ISM concentration measurements with US EPA ISC air dispersion modeling to estimate collection efficiencies at PVLF. The ISC modeling uses the same meteorological and site conditions as occurs during ISM monitoring.

Air Dispersion Mechanism

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 (Equation 1) is shown by the area source dispersion Equation 1-65 within the ISC model documentation (US EPA, 1999):

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

where χ 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 concentration χ in $\mu g/m^3$). V is a term that accounts for the vertical distribution of the Gaussian plume. u_s is the mean wind speed (m/s) at release height. σ_y, σ_z are standard deviation of lateral and vertical concentration distribution (m). D, a decay term accounting for physical or chemical removal processes, is unused as methane is atmospherically stable. Empirical ISC modeling also shows the same linear relationship between the emission rate and the average surface emission concentration 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:

$$E = \frac{ISM_r}{ISM_r + ISM_e} \tag{2}$$

Details of the procedures of this methodology are further discussed in the following sections.[1]

Integrated Surface Methane Monitoring

As described in an earlier study (Huitric and Kong, 2006), the Districts developed an 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 methane is monitored. Methane is easily measured and importantly 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 use an FID with a built-in data logger specifically made for ISM monitoring (a Thermo TVA 1000B was used for this study).

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 is divided into 137 grids as shown on Figure 2. Rule 1150.1 further specifies that each grid be monitored along a sinuous, uniformly spaced 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. 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 51,000 readings for the Main Site are obtained over the 137 grids.

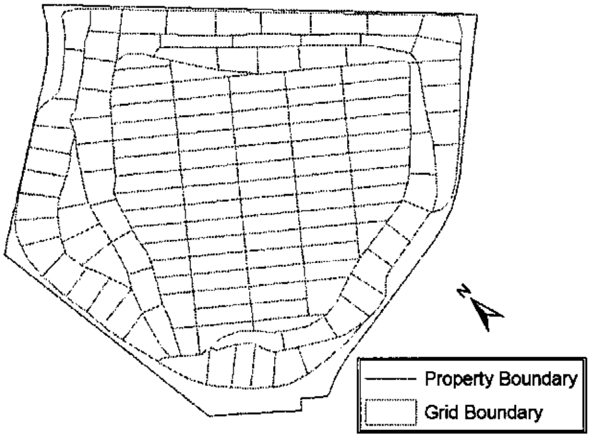

FIGURE 2. Palos Verdes Landfill Main Site ISM grid monitoring layout.

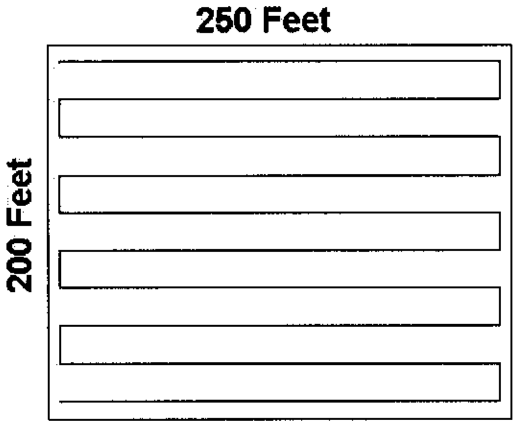

FIGURE 3. Grid schematic with 2,600 foot ISM route.

The SCAQMD specifies that monitoring be performed when wind speeds are 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 rain events and for 72 hours afterwards to avoid atmospheric turbulence and wet soil conditions, which can artificially restrict surface emissions.

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[1] As PVLF is equipped with a comprehensive migration control system, any laterally migrating gases are included in the ISM_r term. As a practical matter, lateral migration rates, for example those reported by Spokas, et al. (2006), are too low to affect the calculated collection efficiency.

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.

FLUX CHAMBER TECHNICAL APPROACH

PVLF operates under the jurisdiction of the California DTSC, which is responsible for ensuring the effective performance of the environmental control systems at the site including those for gas emissions. Though past studies by the Districts showed effective methane emission control, DTSC sought to obtain direct information on emission constituents posing potential health risk (e.g., vinyl chloride, benzene, etc.). Flux chambers were chosen for this purpose as these can accurately measure emission rates of trace constituents.

Though very accurate, flux chambers provide modest spatial coverage. Studies depending solely on flux chambers may require hundreds of measurements, even at small landfills. As a result, researchers have sought to reduce the number of measurements by correlating measured flux rates with more readily available parameters such as cover soil moisture. The success of such efforts may be limited by weak correlation between flux rates and the secondary parameter.

Equation 1 shows that emission concentrations are directly correlated with emission rates. This correlation was advantageously used to prescreen the PVLF surface using concurrent ISM and ISV for locations representing typical and peak emission areas for flux chamber testing. Should peak emission rates exceed conservative screening levels then additional studies would be required to better assess emission exposure. As later described, the flux chambers found no measurable emission rates.

Prescreening

The Districts contracted with SCS Engineers (SCS) to prepare a work plan and to perform the flux measurements at five locations with typical and five locations with peak emission rates. As a guide to expected conditions, SCS used the results of the FY 2001/2002 ISM monitoring program reported above. In accordance with the work plan, the Districts prescreened the 156.3 acres of fill surface within the Main Site in the second quarter 2006 to measure emission levels using Rule 1150.1 ISM procedures augmented with concurrent ISV monitoring. The monitoring was conducted by continuously testing surface emissions across each of the 137 50,000 square foot grids defined for the site. Monitoring occurred only on days preceded by at least 72 hours of dry weather and in accordance with Rule 1150.1 wind speed limits (less than 5 mph 15 minute average wind speed and less than 10 mph instantaneous). Wind speed limits were exceeded on 18 grids; these grids were remonitored.

The prescreening monitoring was performed using a Thermo TVA-1000B unit equipped with an FID calibrated to methane for measurement of total organic compounds (TOC) as well as a PID calibrated to hexane for measurement of VOCs. Locations within grids having high TOC or VOC values were flagged during monitoring.

The data collected from the prescreening round of ISM monitoring were recorded using the Thermo TVA-1000B's internal data management system and subsequently downloaded into a computer for analysis. Over 51,000 pairs of TOC and VOC values were recorded. Grid prescreening results were first ranked according to the work plan using the following criteria:

- Highest average/peak TOC values (ppm as methane)
- Highest number of peak TOC values > 100 ppm
- Highest average/peak VOC values (ppm as hexane)

As the peak TOC value was only 42 ppm, the second criterion was adjusted to the number of peak values above 6 ppm.

The five peak grids were chosen using the following rules:

- Identify top five grids for each criterion
  - Select any grid meeting all three, then...
  - Meeting two then...
  - Meeting one

Two tie breakers were proposed in the work plan to further rank the grids. A proximity tie breaker was used to more highly rank grids situated near residences. The landfill was divided into five proximity zones equally spaced from residences for that purpose. The proximity tie breaker resolved the one observed tie. A second tie breaker, based on the number of peak TOC/VOC values within a grid, was unneeded.

After completion of the 2006 prescreening program, it was noted that there was a significant reduction in TOC levels at PVLF relative to those measured in FY 2001/2002 as summarized in Table 1. By 2006, the average methane decreased to nearly background levels (1.841 ppm), the maximum point TOC value was reduced nine-fold, and the number of instantaneous point values above 10 ppm decreased 15 fold. These reductions followed various ongoing improvements to the collection system to comply with Rule 1150.1 emission requirements. The TOC monitoring results show excellent emission control.

TABLE 1. Comparison of ISM results between FY 2001/2002 and spring 2006.

Period	FY 01/02	2006
Highest Average TOC, ppm CH_4	6.7	2.6
Maximum Point TOC, ppm CH_4	373	42
Points > 10 ppm, %	0.77	0.05

Figure 4 indicates the percent of four-second TOC readings above 4 ppm TOC (as methane) for each grid. Four ppm was chosen as a threshold as these readings are easily measured above the natural methane background. The distribution of detected TOC levels tended to be more frequent over deeper and younger fill areas. Emissions would tend to be higher in such areas due to the greater concentration of generated gases. The TOC results appeared to be useful for identifying flux chamber locations.

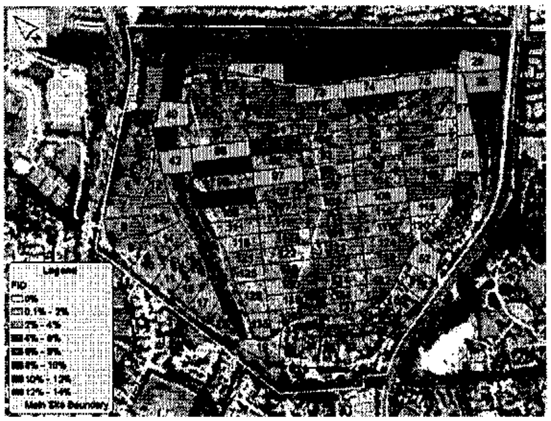

FIGURE 4. Percent of TOC values above 4 ppm CH_4.

The average grid VOC level was just 0.10 ppm as hexane compared to the detector noise level that ranged ± 0.7 ppm. About 90% of the VOC readings fell within the noise level of the detector. The VOC results tended to be at background levels measured upwind of the landfill (near grid 9 in Figure 4). For the fifteen days of VOC monitoring, it was found that the average daily VOC grid level directly correlated with the measured background (i.e., $VOC_g = 0.99\ VOC_b - 0.4$, $r^2 = 0.55$ where "g" and "b" signify the average grid and background levels, respectively). The maximum average grid VOC and maximum point VOC levels were also low (see Table 2).

TABLE 2. VOC prescreening results.

	VOC ppm as Hexane
Average	0.10
Highest Grid Average	1.72
Maximum Point	4.60

Figure 5 presents the percent of VOC point readings within each grid above 0.25 ppm. The 0.25 ppm VOC threshold was chosen as a compromise between the overlap of detector noise (± 0.7 ppm) relative to the low average detected value (0.1 ppm VOC as hexane). The distribution of VOC levels did not correlate with the location of deeper and younger waste deposits as closely as did the TOC values. As later found in the flux chamber study, the monitored trace constituents were well below the PID detection limits. It is unclear precisely to what the PID detector was responding though its direct linear relationship with measured upwind levels suggests that the PID primarily reflected background conditions. Nonetheless it was noted that grid 66, which had one of the highest VOC readings, also had the highest TOC readings (see below). This suggests that higher end VOC values could be useful for selecting high emission grids.

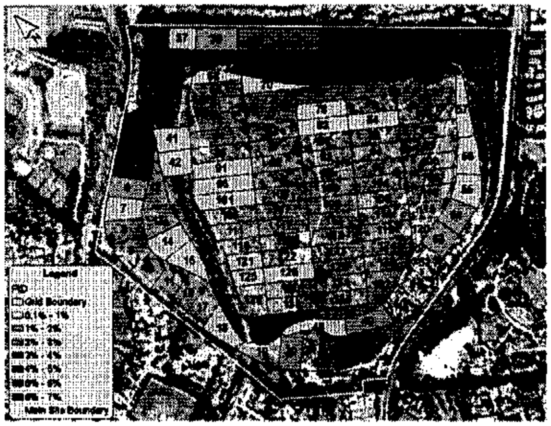

FIGURE 5. Percent of VOC values above 0.25 ppm hexane.

The grid TOC and VOC results were ranked in accordance with the work plan as summarized in Table 3. Grids 66, 27, and 65 ranked uniquely at 1, 2, and 5. Grids 1 and 79 tied but ranked 3 and 4 based on the proximity tie breaker. Within each of the five top ranked grids, "H1" through "H5", the precise locations of the peak TOC and VOC readings had been previously flagged; these locations were used for the flux chamber measurements.

TABLE 3. High emission grid ranking.

	Ranking *(top five grids)*					
Grid	Criteria			Avg	Proximity	ID
	TOC ppm	TOC count	VOC ppm		*(tie breaker)*	
66	2	1	3.5	1	7	H1
27	3	2		2	2.5	H2
1			1	3.5	2.5	H3
79	1			3.5	7	H4
65			2	5	7	H5

In accordance with the work plan, five spatially representative grids were also identified. These grids were selected to represent where the largest percentage of TOC readings falls. For this purpose, the five grids with average TOC levels nearest the median were chosen. The median grid ranked 69th (i.e., (137+1)/2) and grids clustering nearest the median were prioritized as shown in Table 4. DTSC requested that the 66th ranked grid be substituted for the 71st grid to obtain flux results in proximity to receptors. Designations for the spatially representative grids (S1 through S5) are shown in Table 4.

TABLE 4. Spatially representative grids.

Rank	Priority	ID
66th	6	S5
67th	4	S4
68th	2	S2
69th	1	S1
70th	3	S3
71st	5	(not used)

Figure 6 indicates the ten finally selected grids, five high emission grids ("H" prefix) and five spatially representative grids ("S" prefix).

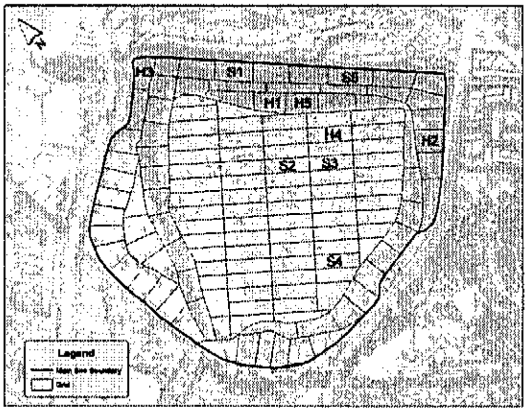

FIGURE 6. High emission (H1 – H5) and spatially representative (S1 – S5) locations.

Static Flux Chamber Design

Ten static flux chambers were installed at the site. The static chamber includes a one-square-meter (1 m^2) stainless steel collar and a lid. The collar was buried about 0.15 meters deep into the landfill surface, and hydrated bentonite was used to seal the soil/chamber interface (Figure 7). The lid includes a fan to mix the chamber headspace, a temperature probe (Omega, TJ36-CPSS-18G-12, Stamford, CT), a pressure probe (Omega, PX654-2.5BD5V), and four outlets for sample collection. Two of the outlets were fitted with Luer connections so that a syringe could be used to extract samples for bulk gas analysis. An additional two outlets were designed with fittings for attachment of SUMMA canisters. The chamber collar has a Viton gasket that was coated with silicone-based grease before each test. The ability of the fan to completely mix the chamber contents in less than 30 seconds has been discussed and verified in a previous study, and was assumed for this test. This was expected to be adequate given the five-minute sampling frequency for methane and 35 minute frequency for trace constituents as described in the following section. Figure 8 depicts static flux chamber sampling.

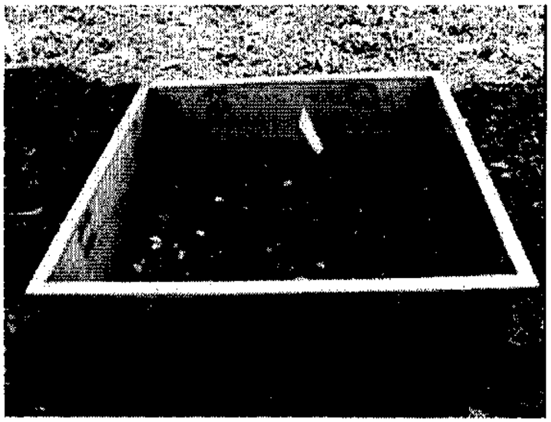

FIGURE 7. Flux chamber collar with bentonite seal.

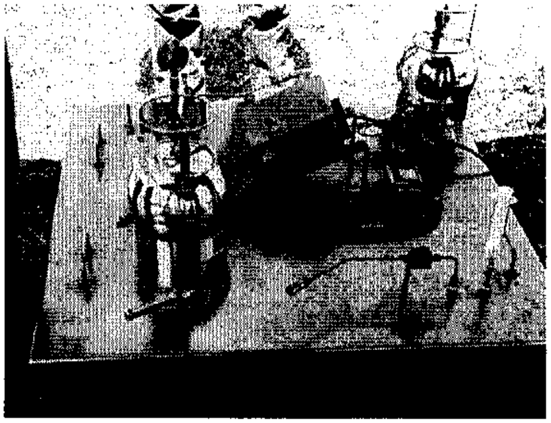

FIGURE 8. SUMMA canister and syringe flux chamber sampling.

Flux Chamber Test

SCS conducted the flux chamber testing at PVLF over a two-day period in August 2006. Chamber collars remained in place over the entire test program while the lids were moved between collars for each test. Collars were buried about 0.15 meters deep, and bentonite was used to seal the soil/chamber interface. Before each flux test, the exact collar depth was measured to calculate the chamber volume, and vegetation inside each collar was trimmed so to not interfere with the mixing fan.

At the start of a test, the lid was placed over the collar with the valves open to preclude an initial pressure increase. After verifying that the fan and gauges were operating properly, the valves were closed to begin a test. Samples were collected in 60 mL plastic syringes equipped with push button valves (Supelco, 5093610, St. Louis, MO) approximately every five minutes for 35 minutes. Field methane analyses were conducted using an on-site Gas Chromatograph (GC) within four hours of sample collection.

The difference between chamber and atmospheric pressure was monitored to verify that sampling did not result in a vacuum. Similarly, the chamber temperature was also monitored to verify that it was not increasing relative to the outside temperature. When tests were conducted during periods of intense sun, the chamber was shaded by a tent to minimize chamber warming. During the test, hourly barometric pressure changes were monitored to confirm that testing conditions did not change during the day of testing.

Samples for speciated organic analyses were collected in evacuated SUMMA canisters (see Figure 8). To avoid inducing a vacuum in the static chamber at the beginning of a test, the time zero sample was collected right after the chamber lid was completely sealed. The lid was then removed to allow the cover and headspace to equilibrate for five minutes after which the lid was replaced and monitoring resumed. The SUMMA canister volume represents about 1.3% of the chamber headspace. The second (final) SUMMA canister sample was collected after the last syringe sample (35 minutes) so that induction of a vacuum did not influence the results.

Analytical Methods

The syringe samples were analyzed for methane at a portable onsite laboratory by H&P Lab using Modified EPA 8015B. The SUMMA canister samples were analyzed for 21 toxic air contaminants (TACs) by Severn Trent Lab using EPA-2 TO-15 SIM (single ion monitoring) technology for low detection limits. The monitored TAC's are listed later in Table 6.

Data Analysis

Trend analysis can be performed for each constituent to determine whether a statistically significant change in concentration occurred. For constituents with significant changes, a flux can be calculated from the flux chamber data using Equation 3:

$$Flux = \left(\frac{V}{A}\right)\left(\frac{\Delta c}{\Delta t}\right) \tag{3}$$

Where, V is the static flux chamber volume (m^3), A is the surface area enclosed by the chamber (m^2), and $\Delta c/\Delta t$ is the slope of a plot of constituent concentration (ppmv) versus time (minute).

Flux data were converted to a mass emission rate by using the ideal gas law. Methane concentration data were only useful if there was a linear trend with time. A non-zero methane flux was reported only if the slope ($\Delta c/\Delta t$) was statistically different from zero ($p < 0.05$). Otherwise, a flux of zero was reported. Equation 3 was also used to calculate TAC fluxes.

Once surface flux is known, collection efficiency for each chemical constituent can then be estimated by:

$$\eta = \frac{F_C}{F_C + F_E} \tag{4}$$

Where, η is the collection efficiency, F_C is the surface emission flux prevented by collection and F_E is the surface flux of the chemical constituent defined by Equation 3. F_C is calculated as the product of the collected landfill gas flow-rate (9254 cfm) and the concentration of the landfill gas chemical constituent (see Table 8), divided by a nominal fill area of 163.9 acres.[2]

With proper unit conversions, surface fluxes and their corresponding collection efficiencies for chemical constituents of interest can then be calculated according to Equations 3 and 4; these are presented in Table 8.

Flux Chamber Results

Final laboratory data of flux chamber measurements were obtained in early October 2006. Methane was measured at five minute intervals over 35 minutes on the ten flux chambers. Only four of the 80 measurements were above the 3 ppm reporting limit. The overall average methane (including values below 3 ppm) was 1.845 ppm, essentially the same as the reported global background for methane in California (1.841 ppm). Though most data were below the reporting limit, trend analysis was performed on the methane levels during the 35-minute test. Table 5 presents the Pearson correlation coefficient and corresponding t statistic indicating the strength of the methane trend for each grid. The correlation coefficients are generally low. The t values are compared with the critical Sidak-Bonferroni t value of 3.82 (i.e., $p < 0.05$ for ten comparisons with six degrees of freedom per comparison). As all t values are less than the critical Sidak-Bonferroni t value, it is concluded that none of the measured methane fluxes are significantly different from zero.

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[2] Actual fill area is 156.3 acres. The nominal area was used for modeling convenience and slightly underestimates collection efficiency by about 0.03%.

TABLE 5. Pearson correlation coefficient and t values for methane flux chamber results.

Location	Pearson r	t
H1	-0.41	1.11
H2	0.61	1.90
H3	0.29	0.75
H4	0.07	0.18
H5	0.81	3.37
S1	-0.43	1.17
S2	0.22	0.56
S3	-0.32	0.82
S4	0.23	0.58
S5	-0.18	0.45

Overall results for the 21 TACs at the start and end (i.e., 0 and 35 minutes) of the flux chamber test are listed in Table 6. Ten compounds were either not detected or detected at levels below the reporting limits. Values averaging below the reporting limit are shown parenthetically in Table 6. Levels detected below reporting limits were used in the statistical summaries and analyses as well as non-detect values, which were treated as zero.

TABLE 6. Flux chamber TAC results.

	Concentration, ppt		
		Time, minutes	
Compound	**RL**[a]	*0*	*35*
1,1,1-Trichloroethane	20	(19.2)[b]	(19.9)
1,1-Dichloroethane	5	(2.1)	(2.2)
1,1-Dichloroethene	10	ND[c]	ND
1,2-Dibromoethane	4	ND	ND
1,2-Dichlorobenzene	45	ND	ND
1,2-Dichloroethane	7	(6.48)	7.8
1,3-Butadiene	10	ND	ND
1,3-Dichlorobenzene	45	ND	ND
1,4-Dichlorobenzene	45	(12.1)	(12.72)
Benzene	47	177.3	126.1
Benzyl Chloride	400	ND	ND
Carbon tetrachloride	10	125	116
Chlorobenzene	20	(0.93)	(2.00)
Chloroform	14	37.3	106.4
m,p-Xylene	40	275.0	176.2
Methylene chloride	120	150.7	124.6
o-Xylene	20	85.30	55.96
Tetrachloroethene	20	43.49	97.40
Toluene	20	727.0	438.7
Trichloroethene	2.5	10.25	8.39
Vinyl chloride	5	ND	(0.37)

[a] Reporting Limit.

[b] Parenthetical values are less than the reporting limit, RL.

[c] Not detected.

Of the eleven detected compounds, chloroform was determined to be a test artifact. Chloroform is not a landfill gas constituent at this site but was found to have originated from chlorinated potable water used for hydrating the flux chamber bentonite seal. It was calculated that the evaporation of just a few milliliters of hydration water during the test was sufficient to produce the measured chloroform levels. The following discussion is based on analysis of the remaining compounds.

Statistical analysis detected no significant changes in flux chamber TAC constituent concentrations between the initial and final samples. This was true whether the results were analyzed together or in groups (day of sampling and "High Emission" vs. "Spatially Representative" grid types). For example, Table 7 presents the Pearson correlation coefficient and t statistic from linear regression analysis for the ten flux chambers. Similar to the methane results, the TAC correlation coefficients were low. As the critical Sidak-Bonferroni t statistic, 3.19, ($p < 0.05$ for ten comparisons with 18 degrees of freedom per comparison) is greater than the tabulated values, it is concluded that no statistically significant trends were detected. Qualitatively, seven of the ten trends were negative indicating that the landfill cover overall tended to degrade ambient air background TAC constituents. Earlier studies (e.g., Bogner et al., 1995, 1997, Chan and Parkin, 2001) have reported such degradation.

TABLE 7. Pearson correlation coefficient and t values for TAC flux chamber results.

Compound	Pearson r	t
1,1,1-Trichloroethane	0.17	0.72
1,2-Dichloroethane	0.22	0.97
Benzene	-0.22	0.95
Carbon tetrachloride	-0.34	1.54
m,p-Xylene	-0.29	1.30
Methylene chloride	-0.33	1.47
o-Xylene	-0.29	1.26
Tetrachloroethene	0.20	0.84
Toluene	-0.28	1.23
Trichloroethene	-0.10	0.44

The collection efficiencies for the constituents in Table 7 were calculated using Equations 3 and 4 to provide a comparison with the efficiency determined by the methane-based ISM/ISC methodology described above. As Equation 4 depends on the landfill gas concentration of each constituent, these are tabulated with the calculated efficiencies in Table 8. The collection efficiency for vinyl chloride is also shown though it was detected in only one of twenty samples. Vinyl chloride and benzene present the greatest potential health risk of any TAC emissions originating from landfill gas.

As shown in Table 8, collection efficiency ranges from about 95 to 102% and is typically 100%. None of these values is significantly different from 100%.

TABLE 8. Calculated collection efficiency for each TAC (these are not significantly different from 100%).

Compound	LFG Concentration, ppb	Collection Efficiency, %
1,1,1-Trichloroethane	13.8	99.9
1,2-Dichloroethane	137.9	100.0
Benzene	4882.2	100.0
Carbon tetrachloride	13.8	101.2
m,p-Xylene	5411.5	100.0
Methylene chloride	26.2	101.8
o-Xylene	1533.5	100.0
Tetrachloroethene	17.9	94.9
Toluene	3585.3	100.2
Trichloroethene	27.6	100.1
Vinyl chloride	481.2	100.0

ISC MODEL APPLICATIONS

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 (e.g., NYSDH, 2000, 2002; Paraskaki and Lazaridis, 2005). Previous ISC model landfill applications predicted gas concentration levels down wind under assumed emission rates. In this and the earlier PVLF study (Huitric and Kong, 2006), 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.

Theoretical background and details about the ISC model can be found in the USEPA document (US EPA, 1999, 2002), and were briefly discussed in previous work on PVLF (Huitric and Kong, 2006).

Meteorology Data

The meteorological data for the study periods were acquired 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 by Trinity Consultants using US EPA's program Meteorological Preprocessor for Regulatory Modeling (MPRM). Mixing heights need to be estimated in order to establish stability categories for the weather conditions. Upper air data at the Miramar airfield north of San Diego (the only full-time station in southern California) and cloud cover data from the nearby Los Angeles International Airport (LAX) were used to calculate the mixing heights during preprocessing.

Preprocessing identifies calms that cannot be modeled. It also increases wind speeds as necessary to a minimum of 1 meter per second (mps) for non-calm periods. The ISC model ignores hours with calm conditions as receptor concentrations cannot be calculated for these. The modeled receptor levels for calm periods are flagged as "0" to show that these should be ignored. No calms were detected in the prescreening meteorological data set.

The ISC model can create exceedingly large output files for hourly meteorological data over a weeks' 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 meteorological file was assigned an arbitrary time stamp of consecutive hours, as the ISC model requires input data to be consecutive in time. These were 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.

PVLF Methane Flow

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 and are monitored at various pitot-tube locations of main header lines. Care has been taken to ensure accuracy in flow readings and to minimize bias in flow measurements. The average methane recovery from the Main Site at PVLF for the second quarter of 2006 was 958 scfm over 163.9 acres or, equivalently, 0.00045 g/s-m^2 in units required by the ISC model.

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 Visual Basic 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 can be used together to calculate gas collection efficiency using Equation 2 for each grid measurement.

Methane as a Surrogate for Risk Drivers

In the ISM/ISC modeling approach, methane is assumed to be a conservative tracer of landfill gas emissions. From a health risk perspective, trace toxics such as benzene and vinyl chloride are the important constituents. There is extensive literature documenting that landfill cover soils can develop a high capacity for methane oxidation by methanotrophic bacteria as well as trace gas cometabolic degradation (Scheutz, et al., 2004). This issue was extensively addressed in a previous study (Huitric and Kong, 2006).

It was shown that important trace toxics, such as benzene and vinyl chloride, oxidize more rapidly than methane within landfill cover soil systems. The flux chamber test reported above showed consistent results between the TACs and methane in that neither had detectable emissions. The ISM/ISC methodology, which relies solely on methane, did detect a slight emission. This indicates that methane as used in the ISM/ISC method is a conservative surrogate for TAC emissions.

Collection Efficiency

During the collection efficiency analyses described in the preceding sections, inspection of the emission reductions (emissions prevented by gas collection), ISM_r, modeled by ISC shows that these are nearly uniformly distributed except near the landfill boundaries. As shown in the previous study (Huitric and Kong, 2006), an approach based on the overall average emissions, ISM_e, and average modeled emissions reduction, ISM_r, provides a much simpler analysis than a more tedious grid-by-grid analysis and is as effective. The averaging approach is also a more conservative approach in estimating collection efficiencies. Table 9 presents the results of such an averaged approach.

The ISC modeled the reduction in surface methane levels (i.e., ISM_r) due to gas collection to be on average 13.396 and 30.702 ppm methane for the Urban and Rural modes, respectively.

The four second Thermo TVA 1000 B readings were averaged for each grid for each monitoring period. The average of all grid readings was 1.886 ppm. Correcting for ambient air background and a slight instrument bias provides an average net emission level (ISM_e) of 0.100 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, 13.496 and 30.802 ppm for the Urban and Rural modes, respectively.

The collection efficiencies, 99.26% for urban mode and 99.68% for rural mode, for PVLF were calculated by Equation 2 (i.e., $E = ISM_r/[ISM_r + ISM_e]$). These high collection efficiency results are consistent with previous studies (e.g., Huitric and Kong, 2006, Spokas, et al., 2006).

TABLE 9. ISM/ISC collection efficiency calculations.

	ISC Mode	
Methane, ppm	**Urban**	**Rural**
Measured LF Surface[a]	1.886	1.886
Calibration Bias Correction	+0.055	+0.055
Actual LF Surface	1.941	1.941
California Air Background[b]	-1.841	-1.841
LF Net Emission (ISM_e)	0.100	0.100
Emissions Prevented (ISM_r)	+13.396	+30.702
Total Emissions Potential ($ISM_r + ISM_e$)	13.496	30.802
Collection Efficiency	**99.26%**	**99.68%**

[a] Excludes values for calm periods that are not modeled by ISC.

[b] Prinn, R. G. and R. F. Weiss (2005). Local background may be higher due to vehicle emissions.

Figure 9 shows the average measured emission levels relative to the average modeled emissions reduction as summarized in Table 9. This graph shows the uncertainty in the ISC model with respect to the Urban and Rural modes. As the actual emissions (0.100 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 level, say 5 ppm ISM_e, would have calculated collection efficiency values of roughly 73% and 86% for Urban and Rural modes, respectively. This indicates that this methodology performs best with high efficiency collection systems but may be much less precise for lower efficiency systems.

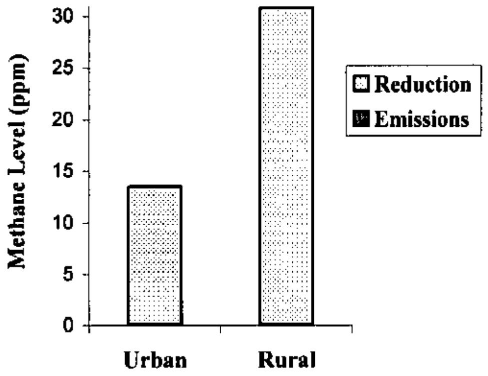

FIGURE 9. Modeled emissions reduction (ISM_r) and measured emissions release (ISM_e) based on Table 9 (the emissions are too small to be visible in this graph).

DISCUSSION

As indicated by Table 9, collection efficiency analysis shows that the PVLF gas collection efficiency exceeds 99% (99.26% for Urban mode, and 99.68% for Rural mode). These high collection efficiency results derived from ISM/ISC technical approach are supported by on-site surface flux chamber measurements. These findings are also in good agreement with collection efficiency field measurements and theoretical analyses reported in earlier studies (e.g., Dr. Stan Zison as reported by Leatherwood, C., 2002, Huitric and Kong, 2006, and Spokas, et al., 2006).

Surface flux chamber measurements found no detectable flux in either the high emission or spatially representative areas at PVLF. Data analysis showed agreement with results of earlier studies (e.g., Bogner et al., 1995, 1997, Chan and Parkin, 2001). Namely, negative flux can be observed for a number of TACs (i.e., the landfill cover was destroying background ambient air TACs). Other TAC's generally varied within the range of background ambient air levels.

The ISM/ISC method is in agreement with and slightly conservative relative to the flux chamber results. As such, the ISM/ISC method may be an attractive alternative to more costly methods that rely solely on flux chambers as the latter have modest spatial coverage and may require hundreds of measurements to quantify emissions.

There may be many landfills where the ISM/ISC approach may be practical. For landfills regulated by NSPS, the data logged by a portable FID unit used for methane monitoring may already be available.

Rule 1150.1 monitoring 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.

Precision is also an issue at sites that may have only moderately effective gas collection efficiencies. This is the case as uncertainties in the ISC model (e.g., Rural vs. Urban modes) become relatively important and have large effects on the calculated efficiency.

A representative weather data set is needed for the ISC model concurrent with ISM 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

In this study, the ISM/ISC method was compared with conventional static flux chamber emission measurements. ISM prescreening was used in Spring 2006 to identify ten locations for flux chamber measurements at the Palos Verdes Landfill. The ten locations were chosen to represent both peak and typical emission areas. The flux chambers were monitored in Summer 2006 for methane at five-minute intervals over 35 minutes. Additionally, chamber samples were taken for EPA TO-15 SIM analysis at the start and end of the 35 minute test.

The ISM/ISC method showed a +99.2% collection efficiency for the 2006 data set. The increase in efficiency from that measured for the fiscal year 2001/2002 data set corresponds to improvements in the gas collection system in the intervening time. The flux chambers found no statistically significant methane accumulation. The flux chamber methane levels were not significantly different from the global background. The initial and final EPA TO-15 SIM constituents were not significantly different from one another. Flux chamber collection efficiencies were calculated to be essentially 100%.

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).

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