Quantifying Capture Efficiency of Gas Collection Systems with Gas Tracers

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KEYWORDS: methane emissions, field measurements, well region of influence

FINAL REPORT

Prepared for the

Environmental Research and Education Foundation

Raleigh, NC

June, 2012

Executive Summary

A new in-situ method for directly measuring the collection efficiency of a gas extraction well was developed. This method requires the injection of an inert tracer gas, a system for measuring this tracer gas in the gas collection well, and accurate measurement of the volumetric flow rate of gas in the gas extraction well during the test. A key to the success of the technique was the use of an on-site photoacoustic field gas monitor to measure the tracer gas in real time.

Thirteen gas tracer tests were conducted within the region of influence (ROI) of a gas extraction well at Yolo County Central Landfill. For 12 tests the gas collection was excellent, always exceeding 70% with eight of the 12 tests showing a collection efficiency exceeding 90%. Here, gas collection efficiency is defined for the point where the tracer gas was injected. Injection points varied from 5 to 15ft in depth for radial distances between 8 and 24ft from the extraction well. These distances are close to the extraction well (D23), since our focus was the development of the gas tracer technology and test durations were shorter if the injection points were near D23. To create more severe conditions for landfill gas (LFG) collection, gas flow from D23 was adjusted downward to decrease the effectiveness of the gas well within the ROI. Even when gas pressures were atmospheric or slightly above atmospheric at the point of tracer injection, gas collection efficiency was very good.

For Test 11 gas collection efficiency was poor – only 7%. Here, the poor efficiency was associated with water-saturated refuse or refuse/ soil located between the point of tracer injection at 5ft depth (MW1-5) and the well screen for D23. Although there was a measureable effect of D23 on gas pressure at MW1-5, the travel path from this point to the gas collection well was likely long and tortuous. This tracer injection point was located within the ROI of D23. Thus, even within an ROI, gas collection efficiency might be poor if gas flow is inhibited, here because of the presence of liquid water. This highlights the need for care when operating landfills as bioreactors, as the addition of liquid or recirculation of leachate may lead to water-saturated conditions in some portions of the landfill.

In addition to conducting gas tracer tests, gas pressures were also measured at all monitoring wells to assess the gas pressure field created by D23. Under ideal conditions, this field is symmetric around the gas collection well. For these field tests, the gas pressure field was not symmetric, with gas pressures along the southern transect much more responsive to D23 than along other transects. Locations with poor gas suction from D23 coincided with the location of Test 11, where tracer recovery was also poor. Thus, measuring the gas pressure field in refuse appears valid for assessing regions of the landfill that might have good or poor LFG collection.

The objective of this project was the development of a gas tracer technology for assessing landfill gas capture efficiency at different points within a landfill. The technology appears best suited for assessing alternative well designs and management practices on landfill gas collection. It may be used to quantify the landfill gas capture efficiency for an entire landfill cell, although the viability of this approach should be tested in future work.

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Introduction

Methane is an important contributor to global warming with a total climate forcing estimated to be close to 20% that of carbon dioxide (CO_2) over the last two decades. The largest anthropogenic source of methane in the United States is “conventional” landfills, which account for over 30% of anthropogenic emissions (U.S. EPA, 2003). However, estimates of the impact of landfills on methane emissions to the atmosphere are not without controversy. For example, a recent study by Spokas et al. (2006) on French landfills concluded that gas collection efficiencies in excess of 90% were achieved with conventional gas collection systems on a landfill with a geomembrane final cover. With gas collection efficiencies this high, fugitive methane emissions for this landfill were negligible, because what methane did escape was mostly oxidized in cover soils. On the other hand, a study recently published in *Environmental Science & Technology* reported that a gas collection efficiency of 70% should be regarded as optimum (Borjesson, et al., 2007). Borjesson et al. (2007) reported results from the stable carbon isotope technique in combination with an optical method that were used to estimate methane budgets (production = emissions + oxidation + recovery) for six landfill sites in Sweden. In discussing the discrepancy between their results and that of Spokas et al. (2006), Borjesson et al. (2007) noted experimental problems with the methods employed by Spokas et al. (2006): the gas tracer flux measurements were performed at the edge of the landfill rather than at some distance, and the grid used for flux box measurements was too coarse and might have resulted in underestimates of methane fluxes by as much as a factor of 10. Borjesson et al. (2007) concluded by noting that “*a more severe problem* (than estimating methane oxidation in cover soils) *is how to estimate the efficiency of the different gas recovery systems*, which calls for more studies in order to categorize them.”

In this work we addressed the “*more severe problem*” noted by Borjesson et al. (2007) - estimating the efficiency of landfill gas (LFG) collection systems. Traditionally, collection efficiency has been computed as recovery/production, where recovery is measured directly from the sum of all gas collection wells, and production is the sum of recovery + oxidation in cover soils + surface emissions. While this traditional procedure works for evaluating the performance of an entire landfill, it is an expensive, indirect measurement that because of cost is usually performed infrequently. In addition, it works for the “whole landfill” and thus cannot be used to assess the efficiency of gas collection from different regions of the same landfill or the utility of a particular gas collection well design, which may be installed at only a few locations.

In this work we developed a new technology for quantifying LFG capture efficiency involving in situ gas tracers. This technology might be used to quantify the benefits of alternative LFG collection systems, to track the efficiency of an existing collection system as a landfill cell moves from active to intermediate to final cover, or to evaluate various operational changes, e.g., modifications to the gas collection system to mitigate the effects on barometric changes on collection efficiency.

Background

Recent In Situ Gas Tracer Tests in Landfills

The project team has conducted 16 gas tracer tests in landfill cells at Yolo County Central Landfill (Yolo County, California) (Yazdani, M.E et al. 2010)and at the Delaware Solid Waste Authority (Sandtown, Delaware) (Han, Jafarpour et al. 2006; Han, Imhoff et al. 2007). The objectives of these tests were to evaluate a new technology for measuring moisture in refuse, the partitioning gas tracer method, and to measure water in different regions of a bioreactor landfill.

A typical tracer test is conducted as follows. With the gas collection system on and operated under standard conditions, tracer gases from a compressed gas cylinder are injected at some location in the landfill, usually with a pulse input as shown in Figure 1(a). The tracer injection typically requires 30 minutes. Following tracer injection, continuous sampling of gas in nearby gas collection wells is performed until the "breakthrough" curve of the tracer(s) is measured. Typical tracer breakthrough curves are shown in Figure 1(b) for two gas tracers. By knowing the mass of tracer injected, the measured breakthrough curve, and the gas flow rate from the extraction well, the fraction of tracer mass collected in the gas collection well can be determined. For the test shown in Figure 1, the collection efficiency was approximately 90% for both tracers, indicating excellent gas capture of the LFG in the vicinity of the injection point. To characterize the overall gas collection efficiency of this well and its region of influence, many tracer tests would be required, with tracers injected at a number of injection points in the refuse at various depths and distances from the extraction well.

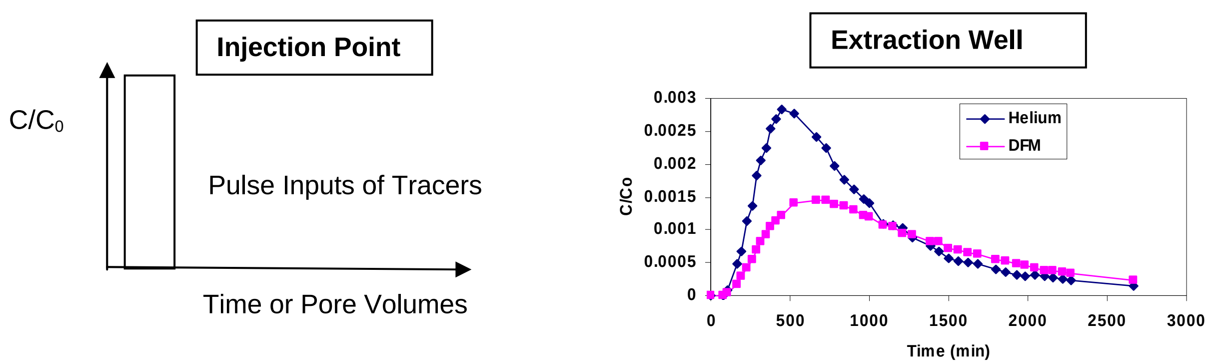


Figure 1 (a) Typical gas injection with pulse input, (b) typical measured tracer breakthrough curves for Helium and Difluoromethane (DFM) tracer gases.

In our first few gas tracer tests in landfills, samples were collected by hand and shipped back to our laboratories for analysis using gas chromatography. While producing quite accurate measurements, this procedure is labor intensive and expensive and limits the number of tests that can be conducted.

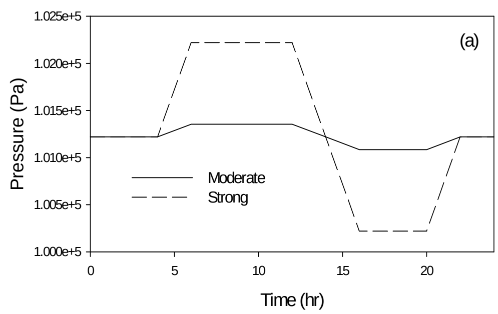
To overcome the cost and manpower needs for tracer measurements with gas chromatography, an INNOVA Model 1412 Photoacoustic Infrared Spectrascope (PAS) (LumaSense Technologies, Denmark) may be used for similar measurements. The PAS operates based on the photoacoustic infra-red detection method. Appropriate optical filters (up to five + water vapor) are installed in the 1412's filter carousel so that it can selectively measure the concentration of up to five component gases and water vapor in any air sample. The 1412's detection limit is gas-dependent, and for our primary tracer of interest, sulfur hexafluoride (SF_6), the detection limit is excellent - 5 ppb. With this instrument, gas analysis can be completely automated. Manpower is only required to inject the tracers, which takes 30 minutes, and then turn on the instrument. The PAS uses an internal pump to collect samples and is programmable, with data saved to a laptop. This instrument was field tested by conducting five gas tracer tests with it in a bioreactor test cell at Yolo County in June 2007. These tests produced excellent results, similar to those shown in Figure 1(b). More recently, the PAS was used in June 2009 to determine the gas flow patterns and methane oxidation rates in pilot scale biocover test cells at Yolo County (Yazdani and Imhoff 2011).

Assessment of Region of Influence of Gas Extraction Well

Any design of a LFG collection system requires an assessment of the region of influence (ROI) of each well. The ROI is affected by the LFG generation rate, which may vary in space and time; the extraction rate at individual wells; the locations of these wells in the landfill; and the degree to which gas can permeate the landfill boundaries. One of the simplest ways proposed to assess the ROI of a pumping well is to measure the gas pressure distribution in the refuse with the well on and off. If there is a measurable difference (within some level of measurement precision) in gas pressure at any sampling point between the on/off conditions, then this point is impacted by the well. However, is this procedure best for determining the ROI, and what is the LFG collection efficiency within such an ROI? Assuming LFG collection efficiency is approximately 100% near the collection well, what is it near the edge of the ROI? For standard vertical wells, where is LFG collection poorest and thus where can improvements be made to increase collection? Is collection efficiency poor only near the landfill surface? Understanding where LFG collection is “good” and where it is “poor” is perhaps the first step to developing improved designs for gas collection systems. However, we are unaware of any measurements that quantify where LFG collection is good and where it is poor within refuse. While we postulate that gas pressures are a good surrogate for such determinations, the in situ gas tracer method may be used to quantify gas collection efficiencies at various points near a test landfill well and compare these results with an assessment of the ROI as determined from pressure measurements.

While an assessment of a well’s ROI might result in specified steady-state suctions applied at well-heads to achieve optimal collection efficiency, what about transients in gas flow? A significant body of literature indicates that barometric pressure changes result in undesired “pulses” of LFG emissions to the atmosphere (Kjeldsen and Fischer 1995; Borjesson and Svensson 1997) (Christophersen, Kjeldsen et al. 2001; Czepiel, Shorter et al. 2003). The impact of barometric pressure effects can be dramatic in some cases. For example, a recent study by Czepiel, et al. (Czepiel et al., 2003) conducted at the Nashua, New Hampshire Municipal landfill found surface methane fluxes increased 300% due to decreases in barometric pressure of 10 millibars, which occurred during passage of low pressure weather fronts over an anaerobic landfill. Thus, a LFG collection system that is manually adjusted on a weekly or monthly basis without consideration of atmospheric pressure changes may result in appreciable fugitive methane emissions.

Our own simulations of LFG flow support these observations. In Figure 2 (a), two variations in atmospheric pressure are shown: a moderate case, where 24-hour average barometric pressure data from Sacramento, California collected for a one-month period were used; and a strong case, where variations in atmospheric pressures measured at the Skellingsted Landfill, Denmark (Poulsen, Christophersen et al. 2003) were selected. The resulting LFG emissions predicted from our LFG model for a hypothetical landfill cell are shown in Figure 2 (b) for two cases: one with a permeable layer installed near the landfill surface to enhance LFG capture and one without. In both cases the gas collection well was operating such that a constant mass flux of LFG was extracted from the landfill. While the existence of a near-surface permeable layer decreased baseline methane emissions from 22 to 15% of the methane generated in the landfill, barometric pressure changes still resulted in emission spikes. It is important to note that these simulations had no "cracks" in the landfill cover: cracking would allow significantly greater fugitive emissions in response to barometric changes, with effects approaching those Czepiel's study (Czepiel et al., 2003).



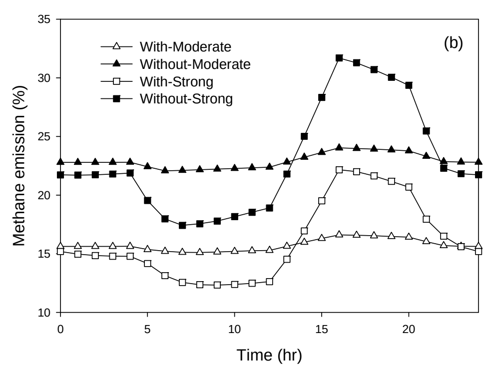


Figure 2 Variations in methane emissions associated with atmospheric pressure changes over a 24-hour period. Results are shown for a landfill with or without a horizontal permeable layer installed at the top of the landfill. (a) Variations in atmospheric pressure; (b) variations in methane emissions, expressed as % of total methane generated in refuse.

Clearly, systems that can mitigate the influence of atmospheric pressure changes on the operation of LFG collection systems will result in reduced emissions and increased collection efficiency. Costs associated with such operations may be offset by the increased revenue from electric generation, if greater amounts of methane are collected and a landfill-gas-to-energy system is in place. The in situ gas tracer method developed in this work may be used to assess alternative gas collection strategies for mitigating the effects of barometric pressure changes. In this study the focus was on the development and testing of the gas tracer technique for quantifying LFG capture efficiency. Future research may utilize the gas tracer test to assess the utility of alternative operational practices to mitigate the impact of barometric pressure effects on fugitive LFG emissions.

Materials and Methods

Overview

The focus of this work was the testing and development of the in situ tracer technique and included the following tasks: (1) design, construction, and installation of field testing equipment, (2) completion of multiple in situ tracer tests under varying pumping conditions and climatic settings, (3) measurement of gas pressure fields for gas tracer tests, (4) measurement of moisture conditions in cover soil, and (5) analysis of in situ gas tracer tests to determine gas well collection efficiency. The procedures and methodologies for the first four tasks are described below.

Field Construction and Instrument Installation

All field tests were conducted in at the Yolo County Central Landfill (Woodland, CA). Tests were conducted on a landfill cell with intermediate cover in the vicinity and influence of a vertical gas collection well – D23. This well is 30 ft long, 4 inch diameter SCH80 PVC pipe perforated at the bottom 15 ft. A schematic of the well design is shown in Figure 3.

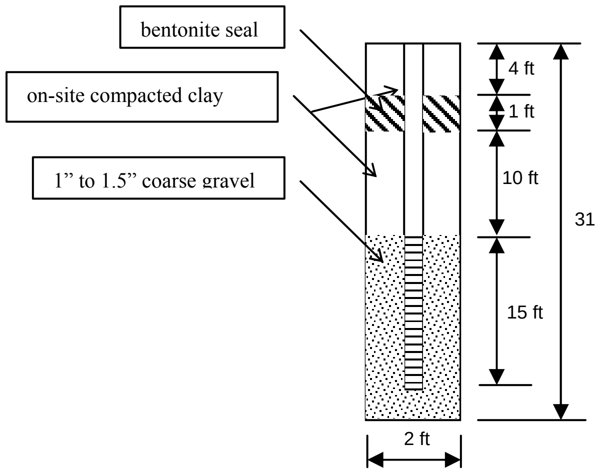


Figure 3 Schematic of vertical gas well used in field tests. Not to scale.

To measure the volumetric flow rate of LFG collected from D23, a ROOTS Meter Series B3 5M175 flow meter (Dresser Inc., Houston, TX) was installed on this well. This meter corrects flow measurements for temperature and pressure and reports the flow rate in standard cubic feet per minute. Electronic output from the meter was recorded remotely in an instrument shed using a supervisory control and data acquisition (SCADA) system. A photograph of this meter is shown in Figure 4.

Figure 4 Photograph of ROOTS Meter Series B3 5M175 flow meter used to measure volumetric gas flow from the extraction well.

Geoprobes were installed in the refuse surrounding D23 to inject tracer gas for tracer tests and to measure gas pressures. Probes were installed in clusters of three, located 5, 10, and 15 ft below landfill surface. Each probe consisted of **3/8” diameter PVC tubing**, which was open

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at the specified depth. The probes were positioned on three lines away from the pumping well as shown in Figure 5. At the landfill surface, the clusters were encased by a small 3-4 ft section of corrugated pipe, which was used to protect probes from animals. Photographs of the installation of the probes are shown in Figure 6. A photograph of the probes and protective pipe at the landfill surface is shown in Figure 7.

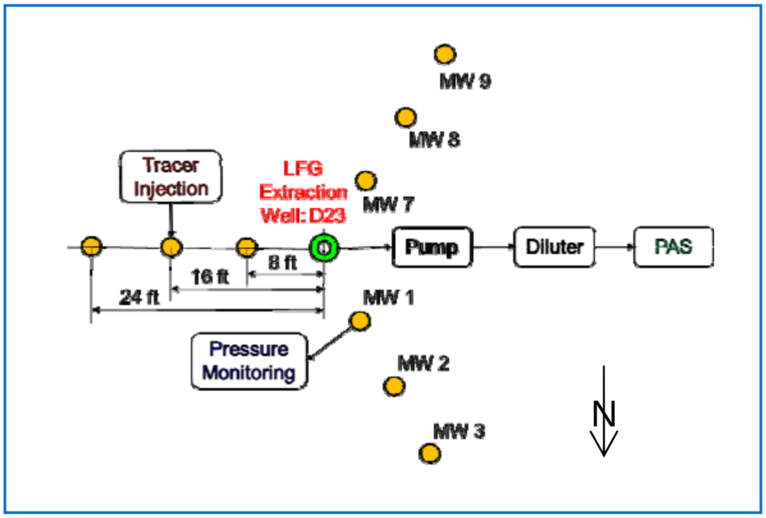

Figure 5 Layout of geoprobes surrounding extraction well D23. Each of the nine monitoring well clusters (MW1, MW2, etc.) contained geoprobes at 5, 10, and 15 ft depth. Monitoring well clusters were located at 8, 16, and 24 ft from D23.

Figure 6 Installation photographs of monitoring wells: geoprobe and access piping (left), and placement of sampling tubing (right).

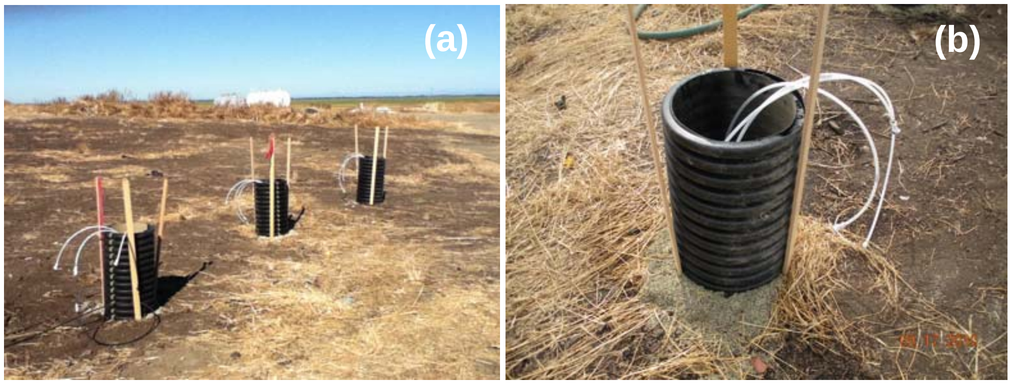

Figure 7 (a) Layout of monitoring well clusters near gas extraction well D23, and (b) close up of one monitoring well cluster. Geoprobe tubing is seen at the top of the corrugated pipes, which were used to protect tubing from animals.

Performance of Gas Tracer Tests

Tracer tests were initiated by beginning continuous measurement of SF_6 from D23 for several hours to establish background readings. A gas sampling tube, **3/8" PVC tubing**, was connected from the well header to the instrument shed. A vacuum pump/condensation removal system was designed for this project and located at the instrument shed. When operating during each tracer test, this system continually extracted a sample gas stream at a flow rate of **approximately 50 mL/min** from the header line on D23 to this instrument shed, where moisture was removed and the gas sample sent to a heated gas diluter (Model 101 California Analytical Instruments, Inc., Orange, CA). Because of the high concentrations of methane and carbon dioxide in the landfill gas, gas samples were diluted with air by a factor of 22 before analysis. An INNOVA Model 1412 Photoacoustic Infrared Spectrascope (PAS) (LumaSense Technologies, Denmark) was used to measure SF_6. The PAS operates based on the photoacoustic infra-red detection method. Appropriate optical filters (up to five + water vapor) are installed in the 1412's filter carousel so that it can selectively measure the concentration of up to five component gases, selected to be methane (CH_4), carbon dioxide (CO_2), sulfur dioxide (SO_2), SF_6, difluromethane (CH_2F_2), and water vapor in any air sample. The 1412's detection limit is gas-dependent, and for our primary tracer of interest, SF_6, the detection limit is excellent - 5 ppb. With this instrument, gas analyses were completely automated. The heated gas diluter, PAS, and laptop used to record data and control the PAS are shown in Figure 8.

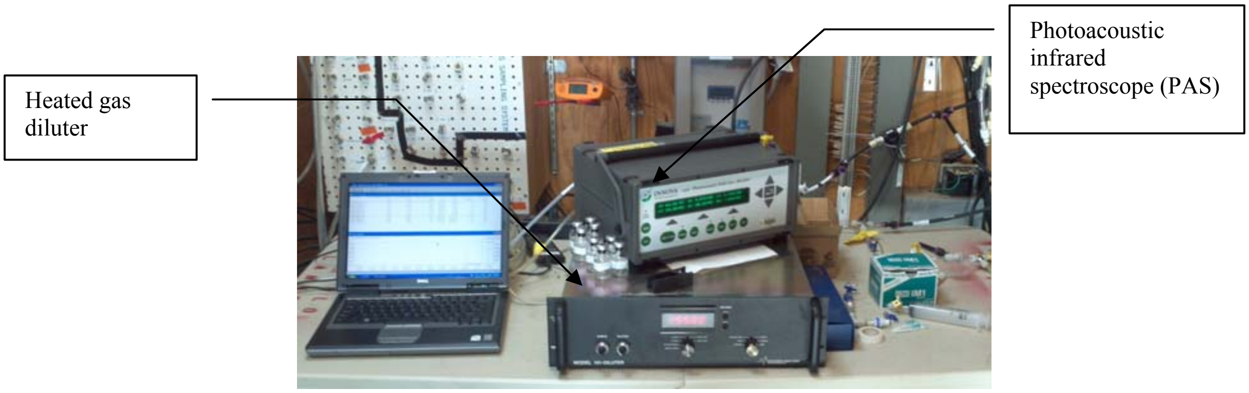

Figure 8 Laptop computer, photoacoustic infrared spectroscope, and heated gas diluter used to automatically measure and record SF_6 concentrations in gas samples.

Once the background signal for SF_6 was established, the tracer test was initiated by injecting a known mass of SF_6 into one of the monitoring well tubes. Injection volumes ranged from 0.1 to 2.0 L: the smaller volumes were injected through tubes nearest D23, while the larger volumes were injected through those farthest away. Gas tight syringes were used to inject pure SF_6 of known volume. To inject 2.0 L, a 3 L adjustable volume aluminum calibration syringe (A-M Systems, Carlsborg, WA) was employed. A photograph illustrating the filling of a 0.1 L syringe in the field from a SF_6 gas bottle is shown in Figure 9. Following the injection of the tracer, three volumes of the geoprobe tubing were flushed with air to displace any remaining tracer gas from the tubing and force it into the refuse.

Following injection of SF_6, the gas flow rate and concentration of SF6 in gas extracted from D23 were measured continuously. Sampling continued automatically round the clock until visual observation of the data plotted on the laptop computer operating the PAS indicated that the entire tracer breakthrough curve had been recorded. The automatic sampling system was periodically checked by technicians, but could be operated overnight without oversight. Simultaneous with these measurements, a sampling pump (Model 35.1.2TTP, KNF Neuberger, Trenton, N.J.), a programmable multi-position electronic actuator and rotary valve (Model EMTAMA-CE, Houston, TX), a gas conditioning and condensate removal system, and a non-dispersive infrared gas analyzer (California Analytical Instrument (CAI) L Series, Orange, CA.) was used to measure gas composition continuously in the extraction well. It was calibrated automatically daily against gas standards (100 percent N_2; 50 percent CH_4, 35 percent CO_2 and 15 percent N_2; 45 percent CO_2, 21 percent O_2 and 34 percent N_2).

Figure 9 Photograph of filling 0.1 L gas tight syringe with tracer gas in field.

Measurement of Gas Pressure Fields

Before and after tracer tests, gas pressures were measured in each of the monitoring tubes and gas extraction well D23 using an gas pressure sensor (model PDM213, Air Neotronics, Oxford, England) with an accuracy of 0.01 inches of water. In addition, the suction on the well was measured continuously using a Model 270 Setra pressure transducer (Setra Systems, Inc., Boxborough, MA), which was housed in an instrument shed and connected with **3/8" PVC tubing** to D23. Gas pressure measurements were used to infer gas flow patterns and the region of influence for D23.

Measurement of Moisture Conditions

Because the surface of a landfill is where uncollected gases "leak", the collection efficiency of any well is directly related to the characteristics of the landfill cover. Compacted Yolo Light Clay soil ~ 20-24 inches in thickness covered the refuse in the vicinity of well D23. Visual observations of this cover suggested that surface cracking was not significant. Instead, any leaking gas would move by advection or diffusion through the soil matrix.

The resistance to advective and diffusive gas flow in the Yolo Light Clay soil is a function of the water saturation or volumetric water content. The volumetric water content of the cover soil was measured using the Moisture Point TDR System (Environmental Sensors Inc., Victoria, Canada). This system consists of moisture point probes that are driven vertically into the soil, which can then measure the volumetric content along a vertical profile using time domain reflectometry. The PRB-A probes used for this project measured the volumetric water content in five segments with lengths of either 15 cm (5.9 inches) or 30 cm (11.8 inches). A schematic of this probe is shown in Figure 10. Because the total measurement length of 142 cm was longer than the soil depth, only the bottom two 30-cm segments were used to record soil moisture. In this case, the probes were driven to the refuse/soil interface. The bottom measurements segment, segment 5, measured the volumetric water content in the bottom 11.8 cm of the soil, from 12 to 24 inches, while segment 4 measured the volumetric water content in the upper 11.8 cm of soil, or the top 12 inches. The other segments were above the soil and so provided no information. TDR probes were installed in the cover beginning in May 2011 with measurements taken approximately once each month. Three probes were available for this field work and normally were positioned near monitoring well clusters 7, 8, and 9 shown in Figure 5. However, these probes were moved to other monitoring well locations in October 2011 and January 2012 to assess the variability of soil moisture.

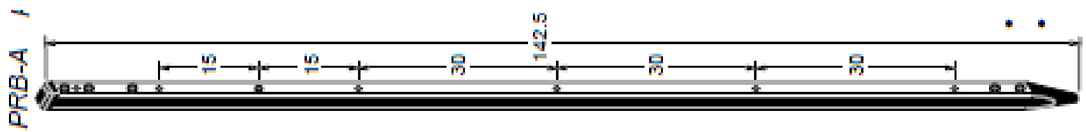

Figure 10 Moisture Point TDR Probe model PRB-A used for measurements of volumetric water content in the soil cover. All dimensions have units of centimeters, and measurements were only made using the bottom two 30-cm long measurement segments. Probe is shown horizontal in this figure, but was installed vertically in the field.

Analysis of Tracer Data

The tracer data were analyzed following methods used previously in landfill tracer studies (Han, Jafarpour et al. 2006; Han, Imhoff et al. 2007; Yazdani, M.E et al. 2010). In this case, since we were only interested in the mass of tracer collected during the tracer test, only the zeroeth moment of the tracer breakthrough curve was calculated. Data were analyzed using MathCAD (Parametric Technology Corporation, Needham, MA), although other mathematical analysis programs could have been easily used, e.g., Matlab, Mathematica, etc. While the calculations could in theory be completed using a spreadsheet program like MS Excel, the analyses are simpler in more advanced mathematical programs.

Results and Discussion

Tracer Tests

To illustrate the results from the tracer tests, an example tracer breakthrough curve at the collection well is shown in Figure 11 for Test 9. In this test, 2 L of SF_6 was injected in MW7-5 when the flow rate at the extraction well was 7.9 SCFM and the measured gas pressure (gauge) at MW7-5 was 0.00 in of water. Data were recorded approximately every minute, which was sufficient to capture the peak arrival of the SF_6. Note that before the arrival of the SF_6 at the gas collection well there was a non-zero signal for SF6. This is a background signal associated with other gases in the landfill. For subsequent data analysis, this background signal must be subtracted from the data.

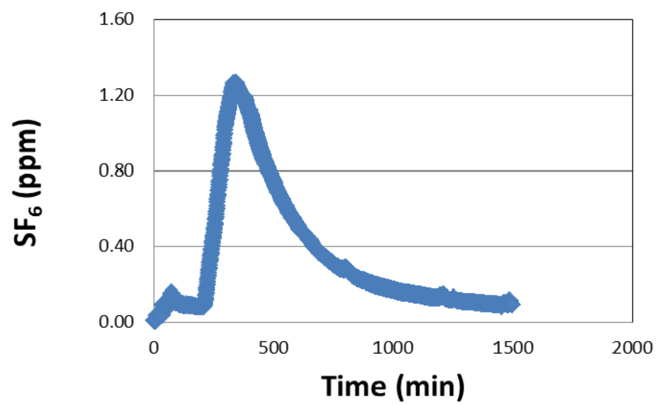

Figure 11 Example breakthrough curve of the tracer SF_6 at the gas collection well. Background signals for SF_6 are above nonzero. Data are from Test 9.

To determine the tracer collection efficiency, the SF_6 concentrations (*C*) in Figure 11 are integrated for the entire breakthrough curve and this is multipled by the volumetric gas flow rate (*Q*) in the well during the collection period. Because *Q* can vary during the test, it must be monitored over the duration of the field experiment. The result is the mass of tracer collected in the gas extraction well. The collection efficiency is then determined from equation (1)

$$\text{Collection Efficiency} = \frac{\int QCdt}{\text{SF}_6 \text{ mass injected}} \qquad (1)$$

A summary of all tracer tests is given in Table 1. Thirteen tracer tests were conducted between 9/2010 and 12/2011, all of which were successful with the exception of Test 7. The SF_6 breakthrough curve for this test is shown in Figure 12A. Here, the background signal for SF_6 changed significantly between the periods before and after the test, which complicated calculations of tracer mass recovery. The variation of tracer background signal is one limitation with this technology, since such variation, if significant, can make it impossible to compute an accurate mass balance for the tracer. While it is sometimes difficult to assess changes in the SF_6 background signal using SF_6 concentrations alone, it is possible to monitor SO_2 concentrations with the PAS instrument, since these are measured simultaneously with SF6. Figure 12B is a plot of SO_2 concentrations for the same time period as the SF6 data. There is clear increase in SO2 with time during this tracer test. In all tracer tests conducted to date, when SO2 concentrations changed significantly during the tracer tests (> 5 ppm) there were also indications that SF6 concentrations change significantly too. Thus, results for SO2 concentrations can be used to assess the stability of the SF6 signal during the tracer test.

Test 1 is unusual in that the gas collection efficiency was 135%. Because it is impossible to obtain a collection efficiency > 100%, this high number must be associated with experimental error. We postulate that the error was large for this test, since it was our first test and we were using the procedure for injecting the SF_6 for the first time.

Table 1 Summary of Tracer Tests

Test	Date	Location	SF_6 Injection Volume (L)	Extraction Rate (scfm)	Collection Efficiency (%)	Gas Pressure (gauge) at Injection Well (in H_2O)	Test Duration (h)
1	9/21/2010	7-10ft	0.1	25.03	135	-0.29	5
2	9/22/2010	7-15ft	0.1	22.74	93	-0.50	7.5
3	9/23/2010	1-15ft	0.1	23.92	103	-0.50	7
4	9/23/2010	7-5ft	0.2	20.58	84	-0.02	17
5	9/24/2010	9-10ft	2	20.80	91	-0.22	30
6	9/26/2010	7-5ft	0.2	7.04	84	0.01	14
8	4/12/2011	7-15ft	2	9.25	73	-0.18	13
9	4/13/2011	7-5ft	2	7.91	94	0.00	25
10	4/14/2011	7-5ft	2	8.98	92	0.00	21
11	6/17/2011	1-5ft	0.5	13.20	7	-0.01	180
12	12/13/2011	8-10ft	1.11	15.84	91	-0.28	42
13	12/16/2011	8-10ft*	1.11	16.42	95	-0.27	50

*Tracer test conducted with wells MW7-5, MW7-10, and MW7-15 all open to atmosphere.

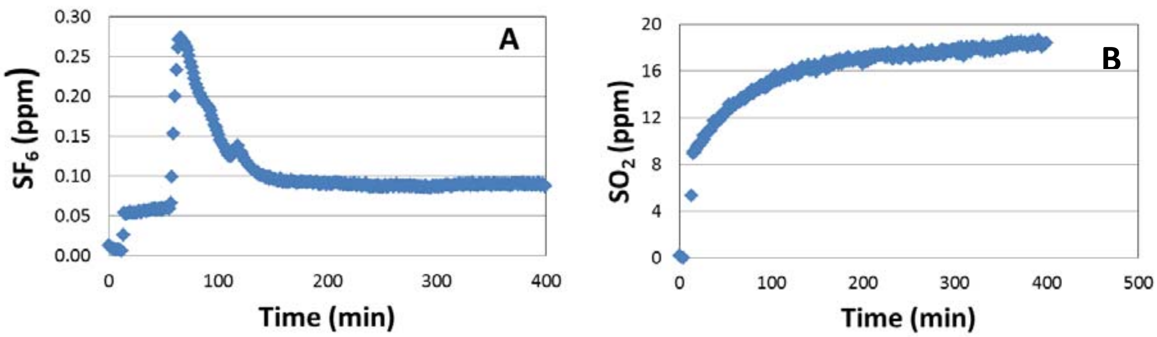

Figure 12 Breakthrough data for SF_6 (A) and SO_2 (B) for tracer Test 7. The non-constant SO_2 data coincide with an increasing background signal for SF_6.

Data in Table 1 illustrate several important points. First, the suction at the gas well was adjusted to achieve different gauge pressures at the points of tracer injection. For example, four tracer tests were conducted for well MW7-5 and the rate of gas extraction varied from 7.0 to 20.6 SCFM over these tests, which corresponded to gas pressures ranging from +0.01 to -0.02 in of water, respectively. By increasing rate of gas extraction, the gas presssure was reducted at this monitoring well, which we anticipated would lead to improved gas recovery. However, the collection efficiency for tracers injected at MW-7 were similar for all four tests, ranging from 84 to 94%, and did not vary systematically with rate of gas extraction or the gas pressure at MW-7. Based on a preliminary analysis of errors associated with the calculation of the collection efficiency, which requires measurements of injected tracer mass, continuous tracer concentrations in the gas collection well, and volumetric flow rate of gas from the extraction well, measurements of collection efficiency are believed accurate to within ± 10%. Thus, a collection efficiency of 84% should be reported as 84 ± 10%. With this level of precision, the collection efficiency of the tracer gases injected at MW7-5 are not significantly different.

The repeatability of the tracer test can be assessed by comparing results on 4/12/2011 and 4/13/2011, when conditions in the landfill and intermediate cover soil were similar. Here, tests for MW7-5 resulted in collection efficiencies of 94 ± 10% and 92 ± 10%, respectively. These data demonstrate that tracer test results were repeatable.

It is also important to note the variation in tracer injection volume for each test. These volumes varied from 0.1 to 2L. Generally, more SF_6 was injected as the gas volume that the tracer would be diluted into increased. If the mass of SF_6 injected is too small, measured SF_6 at the gas extraction well will be below the PAS detection limit and no mass will be recovered, resulting in a collection efficiency of 0%. For this reason, any biases in the tracer method associated with tracer dilution would result in *underestimation* of tracer collection efficiency. If a very large mass of SF_6 were injected, though, the breakthrough curve for the SF6 could take longer to collect.

The mass recoveries of SF_6 presented in Table 1 are also plotted in Figure 13. While the mass recoveries for all tests were generally good (exceeding 70%), the covery for Test 11 was noticeably poor: 7 ± 10%. The SF_6 breakthrough curve for this test is shown in Figure 14. The characteristic single SF_6 peak followed by a long tail did not occur here. Instead, there were two small but sharp peaks at approximately 140 and 170 hours into the test.

The poor recovery for this test is linked to excessive moisture in the vicinity of MW1 and MW2. When collecting gas samples for quantification of CO_2 and CH_4 with a Landtec GEM2000 instrument, separate phase water was extracted from the sampling tubes of MW1-10 and MW3-15. Thus, in the vicinity of MW1-5, more specifically below it, refuse was saturated with water. While a measurable suction was found at MW1-5 before this tracer test (-0.01 in of water), the gas flow to the extraction well was impeded by the water-laden refuse at 10ft depth for MW1 and MW2. Additional data confirming the presence of this water later is provided below in gas pressure measurements.

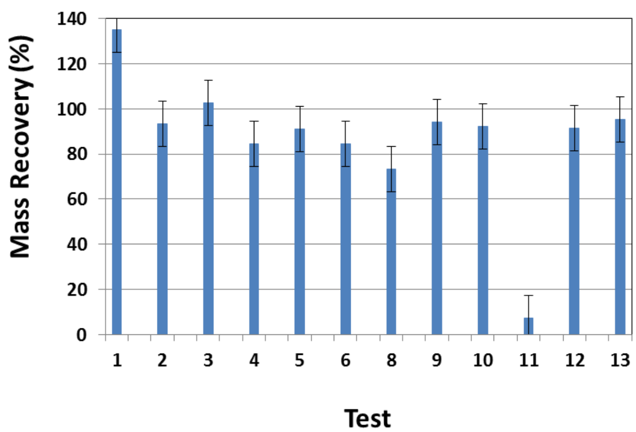

Figure 13 Mass recover for SF_6 for all tracer tests. Details on tracer test location, etc. are in Table 1.

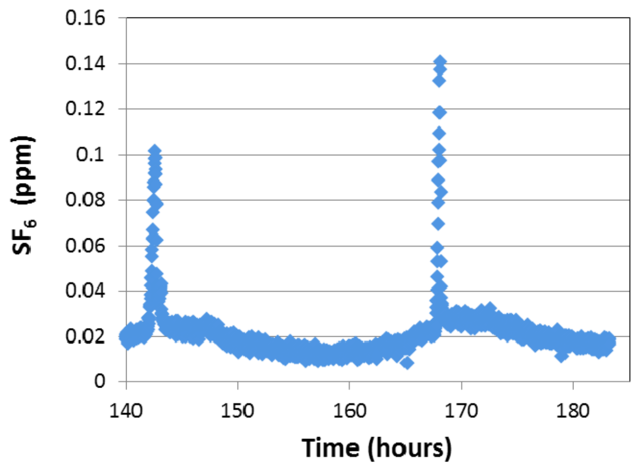

Figure 14 SF_6 breakthrough curve for Test 11. Two small but distinct tracer peaks were observed.

Gas Pressure Field and Region of Influence

For each tracer test, gas pressure was measured at the injection well to assess the impact of the extraction well on the point of tracer injection. These gas pressures are reported in Table 1.

In addition to these data, gas pressures were measured at each of the monitoring wells at multiple times during the testing period. The gas pressure data collected on 6/22/2011, during Test 11, were interpolated in three dimensions using the natural neighbor interpolation algorithm in MATLAB (MathWorks, Natick, MA) and are plotted in Figures 15, 16, and 17. Figure 15 shows three-dimensional perspective plots of the gas pressures; Figure 16 shows vertical slices of gas pressures through monitoring wells 1-2-3, 4-5-6, and 7-8-9; and Figure 17 shows the pressures for horizontal slices at 5, 10 and 15 foot depths. Of the 27 monitoring wells, 13 of them were "clogged" on 6/22/2011 and reliable gas pressure measurements were not obtained. These wells are indicated in Figure 17. For the clogged wells, gas pressures were often positive and exceeded atmospheric pressure. When some of these clogged wells were pumped using a Landtec GEM2000 gas monitor (Landtec, Colton, CA) to measure gas concentrations, liquid water was brought to the ground surface and observed in the monitoring well tubing. Because of these two observations, positive gas pressure and liquid water, we postulate that clogged monitoring wells corresponded to regions of water-saturated refuse or water-saturated mixtures of refuse/daily cover.

From Figure 17, clogged wells are located along monitoring well transects 1-2-3 and 4-5-6. These transects are on the north and east side of gas collection well, respectively (see Figure 5). When installing these wells with a geoprobe, the driller noted increased resistance in these regions at approximately 10 ft depth, which the driller postulated might be associated with a clayey soil. The daily cover soil at the Yolo County Central Landfill comes from surface soil of nearby region, known as a Yolo Light Clay. The properties of this soil are summarized in Table 2 (Lapalla, Healy et al. 1987). It appears that the removal of this daily cover was incomplete along well transects 1-2-3 and 4-5-6, which may have caused perched water and/or water-saturated refuse/soil mixtures. In this case, a continuous gas phase would not exist at these clogged locations, and gas pressure measurements would not be responsive to well suction.

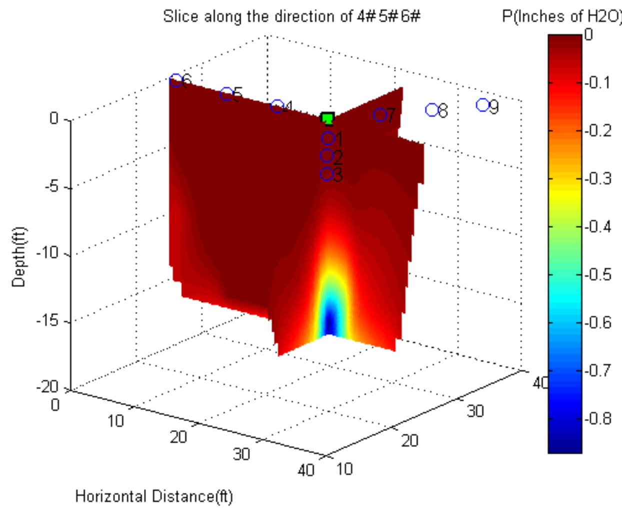

Figure 15 Three-dimensional perspective plot of interpolated gas pressures on 6/22/2011 near the vertical extraction well located at coordinates (25ft, 25ft). The location of the pumping well on the ground surface is indicated with the green square, while the nine monitoring well clusters (MW1- MW9) are shown with blue open circles.

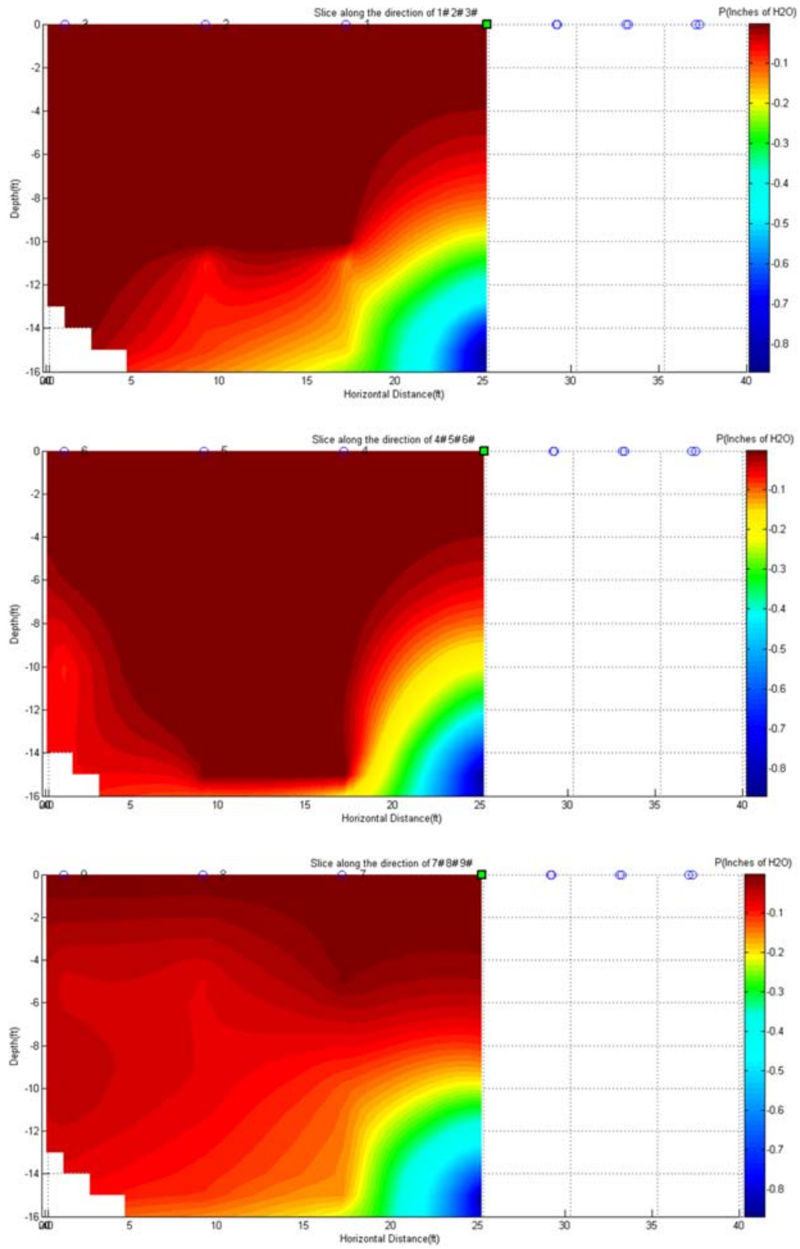

Figure 16 Vertical slices illustrating interpolated gas pressures on 6/22/2011 near the vertical extraction well located at a horizontal distance of 25ft: slice through monitoring wells 1-2-3 (top), slice through 4-5-6 (middle), and slice through 7-8-9 (bottom).

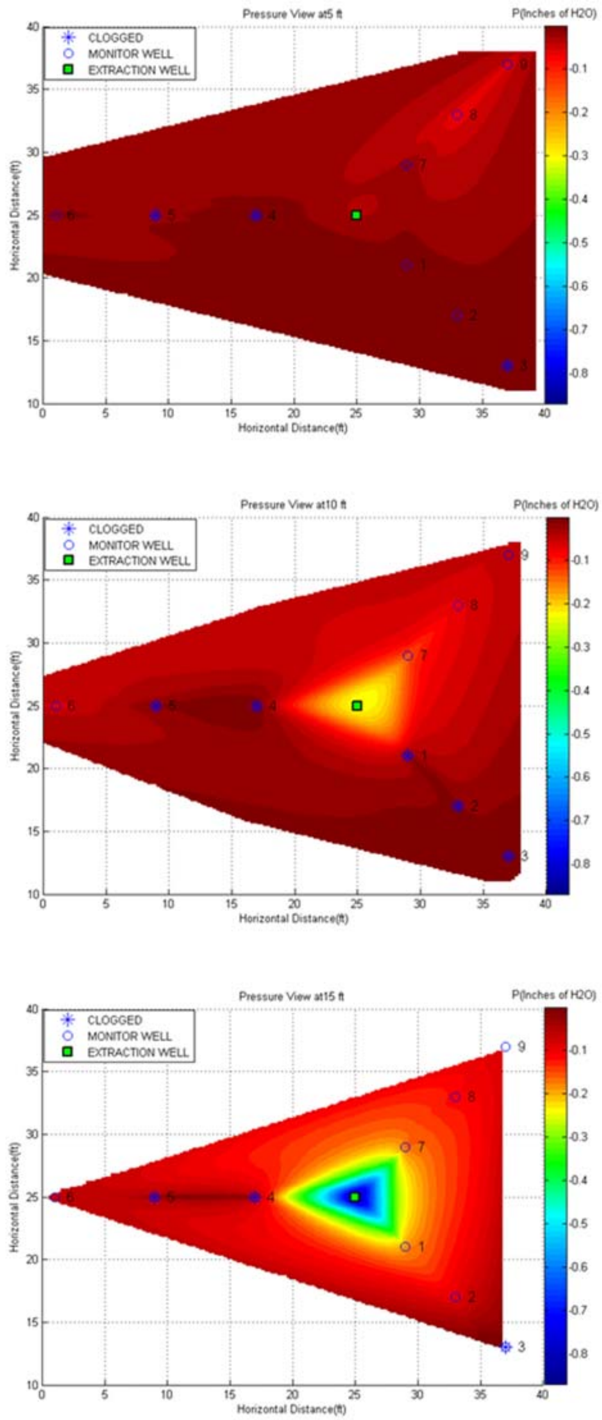

Figure 17 Horizontal slices of interpolated gas pressures on 6/22/2011 near the vertical extraction well located at (25ft, 25ft): slice at 5ft (top), 10ft (middle), and 15ft depths (bottom). Clogged wells are locations where liquid water was believed to have accumulated

Table 2 Soil properties for Yolo Light Clay (Lapalla, Healy et al. 1987)

Property	Value
Saturated hydraulic conductivity (m/day)	0.011
Porosity (-)	0.49
van Genuchten residual volumetric water content (-)	0.175
van Genuchten α parameter (m)	0.401
van Genuchten *n* (-)	1.6

Figures 15-17 indicate that the region of influence for the gas extraction well is clearly not symmetric around the well: gas pressures to the south along monitoring well transect 7-8-9 respond much more to the gas extraction well than gas pressures along the north and east transects. While monitoring well MW1-5 was not clogged (see Figure 15), the monitoring well between it and the gas extraction well (MW1-10) was. Thus, gas flow from MW1-5 to the gas extraction well was likely significantly impeded. Note that the gas pressure field in Figures 14-16 was measured four days after the injection of the SF6 tracer for tracer Test 11 at MW1-5 (see Table 1). Thus, the likely explanation for the very poor recovery of the tracer gas for Test 11 was the presence of perched water and/or a water saturated region of refuse/soil between MW1-5 and the gas extraction well. This perched water and/or water-saturated refuse/soil impeded gas flow.

One objective of this research was to assess the collection efficiency within the region of influence (ROI) of the pumping well, where the ROI is defined according to a methodology established by the US EPA (USEPA 1996). While the outer limit of the ROI was not determined in this work, based on the US EPA methodology the ROI extended beyond all sampling probes used for these tracer tests since negative gas pressures were measured at probes 10ft and 15ft in depth along transect 7-8-9. All but one gas tracer test (Test 11) was conducted in monitoring wells along this transect. Even for Test 11 in MW1-5, negative gas pressures were recorded at MW1-15 (see pressure field contours at 15ft depth shown in Figure 16). Thus, all tracer tests were conducted within the ROI as defined by the US EPA methodology (USEPA 1996). Overall, the recovery of gas for most gas tracer tests within the ROI was very good with the majority of tracer tests showing collection efficiencies exceeding 90% (see Table 1). Recovery was only poor where gas suction from the pumping well was impeded, i.e., MW1-5.

Moisture Conditions of Cover Soil

With the exception of Test 11 at MW1-5, the gas collection efficiency was excellent – even when gas pressures at the point of tracer injection was close to atmospheric (see Table 1). In these cases (Tests 4, 6, 9, and 10), while a pressure gradient existed for gas flow to the extraction well, the tracer injection point was only at 5ft depth where the gas pressure was nearly atmospheric. For these tests, we anticipated poorer gas collection efficiency, since diffusive and even advective flux (Test 6) was possible to the surface. Thus, the excellent collection efficiency was somewhat surprising.

One possible explanation for the efficient gas collection is that the cover soil had a very low gas permeability and a very small effective gas diffusion coefficient. The ability of gas to move by advection or diffusion through a soil is strongly dependent on the volumetric water content. If the volumetric water content is the same as the soil porosity, all pores are filled with water and the permeability of the soil to gas flow is zero. Similarly, the effective diffusion coefficient for gas transport through the soil is also zero for this condition. For both advection and diffusion, gas species (here SF_6) cannot move through the soil unless a continuous gas phase exists. The porosity of the Yolo Light Clay is reported as 0.49 (see Table 1). If volumetric water contents are close to this value, this soil will “seal” the landfill surface well, significantly hindering both advective and diffusive gas transport.

The volumetric water contents of the cover soil were determined using TDR probes from May 2011 through January 2012, and the results are shown in Figure 18. Here, TDR probes were placed adjacent to monitoring wells 7-8-9. All TDR probes indicate dry soil conditions in the top 12 in of soil, with volumetric water contents (volume of water/total sample volume) ranging from 5.2 to 17.2. The volumetric water content for soils 12-24 in depth were much higher, ranging from 30.9 to 61.6. There was a single data point with a volumetric water content of 87.5, which is not physically possible and is believed associated with measurement error. Since the reported soil porosity is 0.49, any volumetric water content that is close to or exceeds 0.49 corresponds to a very wet region with high water saturation. Thus, for the nine month period from May 2011 – January 2012, the bottom of the Yolo Light Clay soil placed on the refuse was nearly water saturated. For these conditions, gas transport by advection or diffusion is significantly limited, which may be one reason for the excellent tracer gas recover for Tests 4, 6, 9, and 10.

In October 2011 and January 2012, the TDR probes were moved to locations near each of the nine monitoring wells to assess the spatial variability of soil moisture. The volumetric water contents for these analyses are shown in Figure 19. For sampling on both dates, volumetric water contents in the top 0-12 in were uniformly small, ranging from 5.8 to 15.0. For 12-24 in depth, volumetric water contents ranged from 17 to 48.3 in October 2011, but11.9 to 35.6 in January 2012. Thus, conditions were wetter with depth, but volumetric water contents were smaller in the 12-24 in depth section on January 2012 versus October 2011.

The 12-24 in depth was drier near monitoring wells 1-2-3 on the north side of the extraction well than the other well clusters in January 2012. However, the cover soil appeared to be 6-12 in thicker in this region, so the TDR measurements near these monitoring wells may not have measured moisture conditions near the refuse/soil interface.

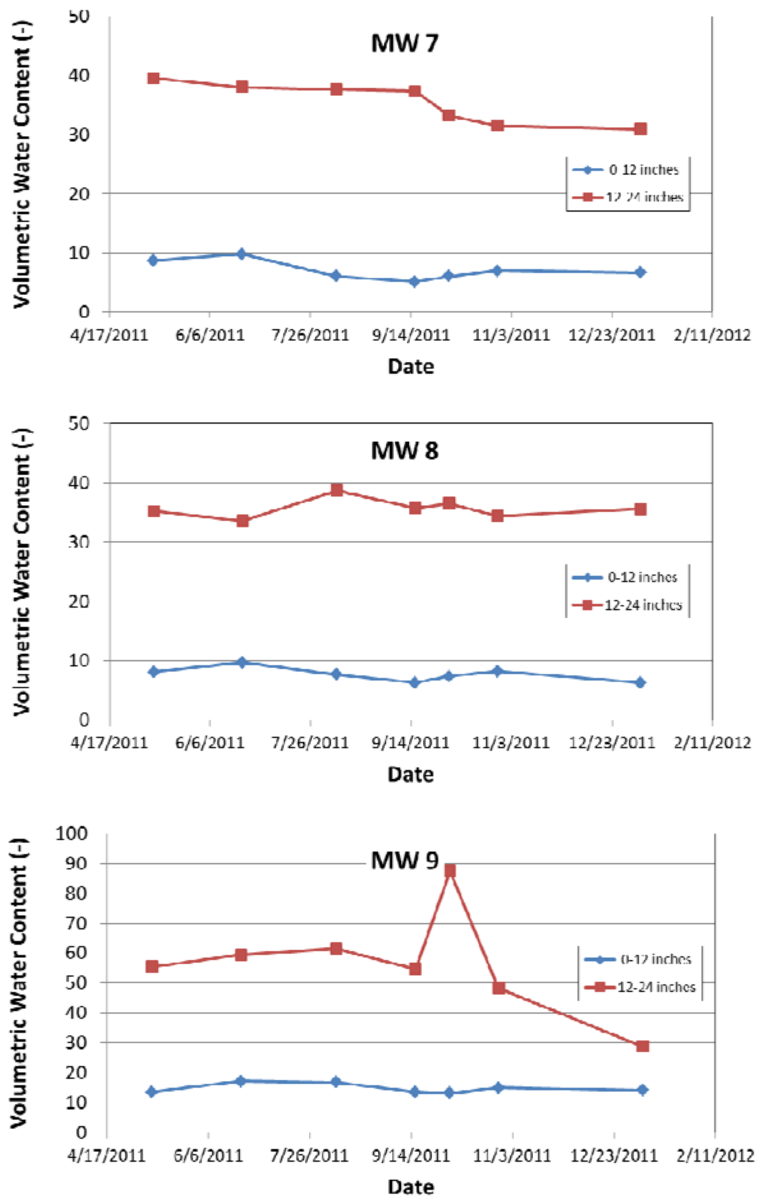

Figure 18 Volumetric water content for soil adjacent to monitoring wells 7-8-9 from May 2011 through January 2012.

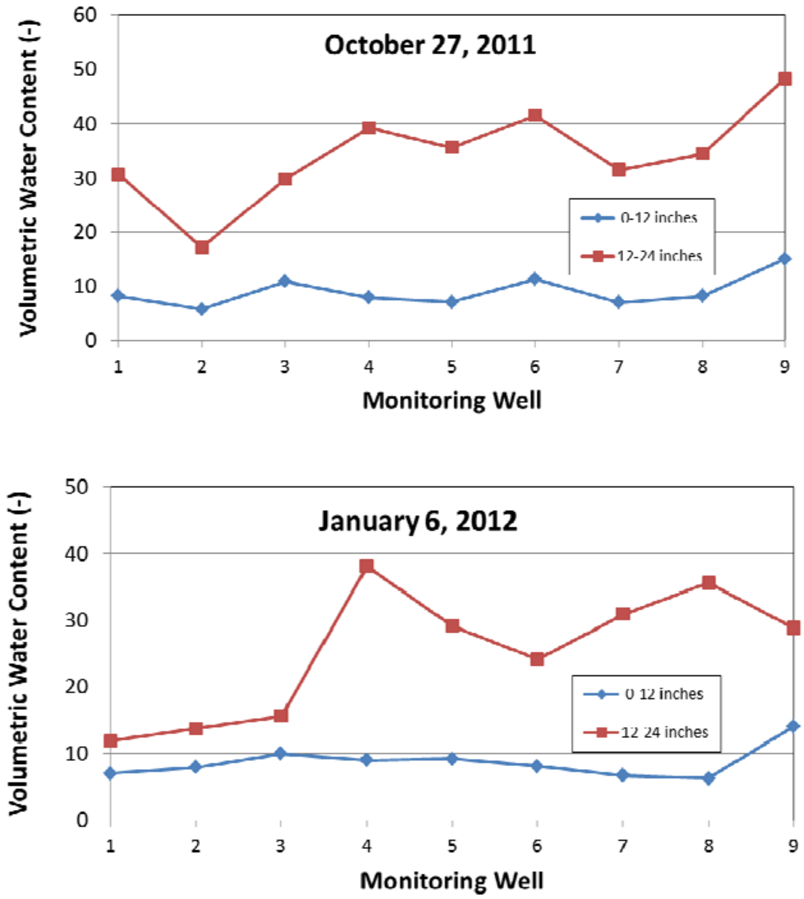

Figure 19 Volumetric water content for soil adjacent to all monitoring wells for two dates: October 27, 2011 and January 6, 2012.

Conclusions

There are several important outcomes from this project that are summarized below.

1) Development and Testing of Tracer Method for Quantifying Gas Collection Efficiency: A new in-situ method for directly measuring the collection efficiency of a gas extraction well was developed. This method requires the injection of an inert tracer gas, a system for measuring this tracer gas in the gas collection well, and accurate measurement of the volumetric flow rate of gas in the gas extraction well during the test. While a detailed cost analysis was not conducted as part of this work, the major equipment expense was the purchase of a sample diluter (Model 101, California Analytical Instruments, Inc., Orange, CA), which diluted the LFG from the extraction well by a factor of 22, and the PAS instrument (INNOVA Model 1412 Photoacoustic Field Gas-Monitor, LumaSense Technologies, Denmark) for measuring the SF_6 gas tracer. These items were purchased in 2007 for $8k and $47k, respectively. Because of the advancement in technologies for measuring trace gas constituents, alternative technologies may be available soon that might enable measurement of a tracer gas using less costly equipment.

   A key to the success of the gas tracer technology was the use of SF_6 as a tracer. Because SF_6 is a potent greenhouse gas and subject to increasing regulation, it may be more difficult to use it in landfills in the future, even in trace amounts. Future work should involve the testing of alternative tracers to comply with environmental regulations. One possible class of tracers are perfluorocarbons, which can be measured with the PAS and have been used as replacements for SF_6 in other work.

2) Assessment of LFG Collection Efficiency in Extraction Well Region of Influence: Following the US EPA's methodology for defining the region of influence (ROI) for a gas extraction well (USEPA 1996), all 13 of the gas tracer tests were conducted within the ROI of well D23 at the Yolo County Central Landfill. For 12 of these tests the gas collection was excellent, always exceeding 70% with eight of the 12 tests showing a collection efficiency exceeding 90%. Here, gas collection efficiency is defined for the point where the tracer gas is injected. Injection points varied from 5 to 15ft in depth for radial distances between 8 and 24ft from the extraction well. These distances are close to D23, since the focus of this project was the development of the gas tracer technology and test durations were shorter if the injection points were near D23. To create more severe conditions for LFG collection, gas flow from D23 was adjusted downward to decrease the effectiveness of the gas well within the ROI. Even when gas pressures were atmospheric or slightly above atmospheric at the point of tracer injection, gas collection efficiency was very good (see Table 1).

   For Test 11 gas collection efficiency was poor – only 7%. Here, the poor efficiency was associated with water-saturated refuse or refuse/ soil located between the point of tracer injection at 5ft depth (MW1-5) and the well screen for D23. Although there was a measureable effect of D23 on gas pressure at MW1-5, the travel path from this point to the gas collection well was likely long and tortuous. This tracer injection point was located within the ROI of D23.

3) Relationship between Collection Efficiency and Gas Pressure Field: In addition to conducting gas tracer tests, gas pressures were also measured at all monitoring wells to assess the gas pressure field created by D23. Under ideal conditions, this field is symmetric around the gas collection well. For these field tests, the gas pressure field was clearly not symmetric, with gas pressures measured along the southern transect (monitoring wells 7-8-9) much more responsive to D23 than those along other transects. The extraction of liquid water from some monitoring wells suggests that the asymmetric distribution of gas pressure was associated with water-saturated refuse or refuse/soil. Gas collection efficiency was always high along the southern transect, but was very poor for the test conducted in MW1-5 along the northern transect, where water-saturated conditions were believed to exist. Thus, even within an ROI of an extraction well, gas collection efficiency might be poor if gas flow is inhibited, here because of the presence of liquid water. This highlights the need for care when operating landfills as bioreactors, as the addition of liquid or recirculation of leachate may lead to water-saturated conditions in some portions of the landfill.

4) Importance of Cover Soil on Gas Collection Efficiency: Measured gas collection efficiencies were high at MW7-5 (5ft depth), even when the extraction rate at D23 was turned down and gas pressures were atmospheric or slightly above atmospheric. In this case, we expected gas collection efficiency to decrease, but it remained > 80% (see Table 1). Measurements of the volumetric water content indicate that the cover soil had a high water saturation at 12-24 in depth along monitoring well transect 7-8-9. When water saturations are near the soil porosity, as were these data, gas permeability and effective gas diffusion coefficients are small. Thus, one possible reason for the excellent gas recovery near the landfill surface for MW7-5, even when D23 well suction was reduced, was the sealing of the cover soil.

5) Potential for Future Applications: The primary objective of this project was the development of a gas tracer method for quantifying the collection efficiency of gas collection wells. In the tests conducted here, a small volume of gas tracer was injected sequentially at different locations in the landfill cell, and the mass collected from each test used to assess the collection efficiency at different injection points. While this procedure allowed the measurement of collection efficiency at multiple points in the landfill, it required many tests with some tests requiring multiple days and one test over two weeks.

   If the objective is to determine the gas collection efficiency for an entire landfill cell, the tracer test should be conducted differently: tracer should be injected at a representative number of locations within the landfill cell at the same time – injecting more tracer gas at locations farther away from the extraction wells, and less at closer locations. Then, the breakthrough curves of all tracer injection points would be measured simultaneously at the header pipe for the landfill cell. The test duration would be dictated by the travel time from the farthest injection points to the gas collection wells. Such a test would provide an integrated measure of LFG collection efficiency for the landfill cell.

Another objective that may be better suited to this technology is to use tracer tests to assess alternative well designs and management practices. For example, gas tracer tests could be used near wells with and without synthetic “boots” to assess the impact of boot diameter and material on LFG capture. Tracer tests might also be used to quantify the effect of adjusting LFG well suction in response to barometric pressure changes on collection efficiency, which has been proposed to reduce LFG emissions. Quantitative data from tracer tests would help assess the utility and cost-effectiveness of alternative well designs and management practices.

In this work we demonstrated the utility of gas tracer tests for quantifying LFG capture at particular locations within a landfill cell. While there are certainly limitations to this technology, this method may be a valuable tool to help answer questions related to LFG collection efficiency and gas flow within landfills.

Acknowledgments

We thank the Environmental Research and Education Foundation for their financial support of this work. Dr. Bryan Staley's support and comments on this research are also acknowledged. Charlie Barrett and Dan Rebey, staff at the Yolo County Central Landfill, provided important assistance in the installation and maintenance of field instrumentation and in gas pressure and composition measurements.

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