A Method for Estimating the Rate of Landfill Gas Generation By Measurement and Analysis of Barometric Pressure Waves

Harold W. Bentley, Ph.D.
Hydro Geo Chem, Inc.,
51 West Wetmore Road, Tucson, Arizona 85705
haroldb@hgcinc.com

Stewart J. Smith, M.S.
Hydro Geo Chem, Inc.
51 West Wetmore Road, Tucson, Arizona 85705
stewarts@hgcinc.com

Jinshan Tang, M.S.
Hydro Geo Chem, Inc.
51 West Wetmore Road, Tucson, Arizona 85705

Gary R. Walter, Ph.D.
Hydro Geo Chem, Inc.
Hydro Geo Chem, Inc., 51 West Wetmore Road, Tucson, Arizona 85705

Abstract: Estimation of the rate of landfill gas (LFG) generation is needed (1) to satisfy USEPA and state regulatory requirements associated with estimating non-methane organic carbon emissions; (2) to assess the impact of landfill-generated methane on global warming; (3) as part of the design of LFG and methane control systems; and (4) to provide information necessary to evaluate and design LFG-to-energy projects. Current methods for estimating LFG generation are not sufficiently accurate to reliably meet these needs. In the first case, inaccurate estimation of LFG generation rate can lead to installation of a costly and unnecessary LFG collection system. For the second, third, and fourth cases, the reliability of the estimated LFG generation rate is critical to technical and/or financial project success.

This paper presents an improved methodology for estimating the LFG generation rate called the "baro-pneumatic method". The baro-pneumatic method is based on the recognition that the rate of landfill gas generation can be determined with reasonable engineering accuracy by analysis of the transient pressure responses at depth in the landfill to natural variations in barometric pressure. The method consists of monitoring atmospheric pressures at landfill surface and subsurface pressures in the landfill (and, where appropriate, in surrounding soils) over a period of 2-5 days. The pressure monitoring data are then used to calibrate a site-specific, distributed-parameter gas flow model of the landfill based on Darcy's Law and the continuity equation. LFG generation rates and gas permeabilities of the refuse, cover, and soils are varied to match the observed atmospheric pressures

at the landfill boundary to the pressures observed in the refuse and soils. Examples of baro-pneumatic testing at several landfills suggest that baro-pneumatic estimates of LFG generation rate more reliably predict LFG recovery rates actually achieved by LFG collection systems than estimates by other methods.

Keywords: landfill gas; baro-pneumatic; landfill gas estimate, landfill gas modeling, landfill gas collection, LFG-to-energy

Introduction

Estimation of landfill gas (LFG) generation rates is conducted (1) to satisfy USEPA and state regulatory requirements associated with estimating non-methane organic carbon (NMOC) emissions; (2) to assess the impact of landfill-generated methane on global warming, (3) as part of the design of LFG and methane control systems; and (4) to provide information necessary to evaluate and design LFG-to-energy projects.

Regulatory-required estimation of NMOC emissions is based on a progressive 3-tier approach specified in 40 CFR Subtitle D which includes either predictions by the indirect EPA 1st-order decay LandGEM model (Pelt and others, 1998) or direct measurement by the Tier 3 procedure detailed in 40 CFR Chapter 1, Part 60, Appendix H. Design of LFG collection systems for LFG control or LFG-to-energy projects includes developing estimates of LFG production and projecting these estimates into the future. The estimates are necessary to quantify the design goals of the gas collection system, to assess capital needs, and, in the case of LFG-to-energy projects, to determine potential revenues. The LFG estimation methodology commonly employed is based on analytical 1st-order or modified 1st-order decay models (SCS and Augenstein, 1997) that are similar to the LandGEM model.

Neither direct nor indirect methods appear to provide sufficient accuracy to reliably estimate NMOC emissions, design LFG control systems, or provide useful measures of the available energy resource for LFG-to-energy systems. LFG generation estimates obtained by the empirical 1st-order decay models are regarded as uncertain due to the problems regarding variation in LFG production owing to variable water content, temperature, presence or absence of buffering agents, nutrient levels in the waste, and waste compaction (SCS and Augenstein, 1997), limited-accuracy input parameters (Pelt and others, 1998); and inability to validate estimates owing to lack of or inaccuracy of site-specific measurement procedures. Regarding direct measurements, Walter (2003) determined that the Tier 3 LFG estimation method is technically flawed and its estimates are unrelated to LFG production rates (Walter, 2003). Walter concluded that the LFG generation rate cannot be determined from extraction well testing and pressure monitoring without employing the known or reasonably estimated pneumatic properties of the landfill.

Description of the Baro-pneumatic Method for Estimating LFG Production

We present here a new, direct measurement method for estimation of landfill gas generation termed the baro-pneumatic method. Unlike other direct or indirect techniques, the baro-pneumatic method is site-specific and based on quantitative gas flow principles. The method is relatively inexpensive and efficient to perform. This approach also provides independent estimates of the gas permeability of the cover, refuse, and surrounding native soils—data that can be of significant value in designing efficient landfill gas collection or control systems.

The baro-pneumatic method is based on the recognition that pressures in landfill refuse and surrounding soils are affected by both the sub-surface production of LFG and the pressure variations in the atmospheric pressure that propagate through the landfill and that the rate of landfill gas generation can be determined with reasonable engineering accuracy by analysis of the transient pressure responses at depth in the landfill to natural variations in barometric pressure. The method consists of monitoring barometric pressures for several days at the surface of the landfill and subsurface pressures (response pressures) over the same time period at points within the landfill. In the case of unlined landfills, response pressures may also be measured in native soils below and/or to the side of the landfill. Displayed as plots of pressures vs. time, these data exhibit transient changes in response pressure that are delayed in time, reduced in amplitude, and increased in average pressure relative to the transient changes in barometric pressure. As shown below, these effects depend on landfill geometry, permeability and porosity distribution, and LFG generation rates. Analysis of these transient changes using models based on well-established pneumatic equations provides the desired estimates of LFG generation rates as well as estimates of gas permeability distribution of the landfill (and surrounding soils).

Theoretical Basis for the Baro-pneumatic Method

LFG generated within a landfill will flow through the landfill materials until it escapes through the cover, sides, and bottom of the landfill. For lined landfills, gas escape is primarily through the cover materials.

The average gas pressure at a given depth and location within the landfill is determined by Darcy's Law:

$$\vec{q} = -\frac{\overline{\overline{k}}_e}{\mu}\left(\nabla P + \rho g \vec{n}\right) \qquad (1)$$

where $\vec{q}$ is the gas volumetric flux vector; $\overline{\overline{k}}_e$ is the effective gas permeability tensor; P is the pressure at a point in the refuse; μ is the gas dynamic viscosity; ∇ is the gradient operator; ρ is the gas density; g is the gravitational acceleration; and $\vec{n}$ is the unit normal vector (downward).

Although the effective gas permeability, viscosity, and density are dependent on temperature, pressure, and gas composition, in many practical situations at landfills, these parameters can be treated as constants for the purpose of estimating the LFG generation rate. If greater accuracy is required, mathematical models that account for the variation in gas properties can be used.

Based on equation (1), the average pressure in a landfill that is generating LFG will be greater than average atmospheric pressure (all pressures corrected for elevation of the pressure measuring point). Equation (1) also implies that the rate of LFG generation can be computed from measurements of the difference between atmospheric pressure and pressure in the landfill if the effective gas permeability and viscosity are known or can be reasonably estimated. Performing such an analysis is complicated, however, by the fact that atmospheric pressure is constantly changing. The changes in atmospheric pressure propagate through the landfill cover, refuse, and surrounding soil, causing the gas pressure in the refuse to continuously vary from its average value.

The variation of the internal pressure at a given location due to changes in atmospheric pressure depends on the effective gas permeabilities and gas-filled porosities of the cover, refuse, and surrounding soil and on the dimensions and shape of the landfill. To the extent that atmospheric pressure variations can be approximated by a simple harmonic function, analytical equations can be used to estimate the pneumatic diffusivity of soils and other subsurface materials (e.g. Weeks, 1978; Rojstaczer and Turk, 1995, Chan, 1995; Lu, 1999). These equations show that the pressure response at depth z depends on the pneumatic diffusivity k_e/ϕ, where ϕ is the gas porosity of the soil, that the amplitude of the pressure response at depth z is attenuated with respect to that of the atmospheric pressure wave as a function of k_e/ϕ, and that the pressure wave at depth z lags behind the pressure wave at the land surface as a function of k_e/ϕ.

However, the conditions for estimating real world LFG generation rates from the atmospheric pressure response are not as simple as those assumed in deriving and applying these analytical equations. First, atmospheric pressure varies in response to a number of factors and cannot generally be described by simple harmonic functions. In addition, the pressure responses in a landfill depend on the soil and refuse pneumatic properties, which are not uniform in space. The pressure response also depends on the geometry of the landfill and the location of the pressure measurement points. Finally, the difference between the average internal pressure and the average atmospheric pressure is difficult to accurately determine because both pressures are constantly changing. These complexities will usually require the use of a numerical model to derive the effective gas permeability and LFG generation rate from the measured atmospheric pressure and subsurface pressure response.

A suitable mathematical model would solve a partial differential equation based on Darcy's Law for gas flow and the continuity equation. One formulation of such an equation is:

$$\nabla \bullet \frac{-\overline{\overline{k}}_e \rho}{\mu}(\nabla \mathrm{P} + \rho g \bar{n}) = \phi \frac{\partial \rho}{\partial t} + \rho \dot{Q} \qquad (2)$$

where $\dot{Q}$ is the volumetric rate of gas generation per unit volume of the porous medium; ϕ is the gas-filled porosity; t is time, and the terms k_e, μ, and ρ are dependent on the temperature, pressure, and gas composition.

Various simplifications to equation (2), such as but not limited to assuming that k_e, μ, and ρ are constant, are also possible depending on the circumstances at the site and the desired level of accuracy. Another simplification in (2) is to eliminate the density term by using the Ideal Gas Law or various adjustments to the Ideal Gas Law for real gases to express equation (2) in terms of pressure or pressure squared.

The only factors affecting gas pressures at fixed measuring points within the fill in the short term will be changes in boundary pressures related to changes in barometric pressure, changes in gas permeability and gas porosity, and changes in LFG generation. Only the first of these, changes in boundary pressure resulting from barometric pressure fluctuations, would be expected to create changes in pressure within the landfill within the short time (2-5 days) required to conduct a baro-pneumatic test. An exception would be a significant rainfall event that might create a reduction in average gas permeability or porosity of cover materials.

Thus, when coupled with boundary conditions describing the variation of atmospheric pressure at the land surface, solutions to equations based on equation (2) provide the basis for determining the LFG generation rate solely from the measurements of atmospheric and subsurface pressures using modeling and parameter estimation procedures.

Field Baro-pneumatic Measurements

The field baro-pneumatic measurement process is illustrated in Figure 1, a schematic cross section of a landfill equipped with pressure sensors and a data acquisition system. Probes tipped with gas permeable screens are implanted in the landfill. Multiple-probe strings of implants can be installed in a single borehole to provide a vertical pressure profile. The locations, depths, and number of implants suitable to conduct the test depend on the complexity and size of the landfill and can be estimated based on professional judgment or assessed by sensitivity analysis utilizing a preliminary model.

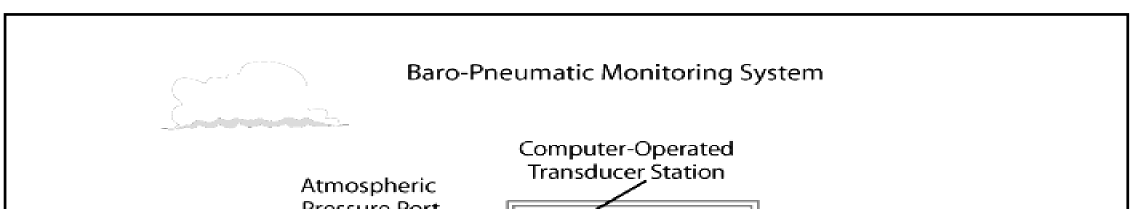


Figure 1. Schematic of baro-pneumatic monitoring system

An accurate and sensitive pressure monitoring system monitors these probes. The rate of LFG generation, the effective gas permeability of the refuse, cover, and surrounding soil, and the range of atmospheric pressure variations determine the required precision of the pressure-measuring device. The data described in this paper were obtained by a monitoring system consisting of a sensitive pressure transducer (Setra, Model 370) capable of determining gas pressure to an accuracy of better than 0.05 mm Hg, a Valco 16-port valve that connects a number of probe implants to the transducer via small diameter plastic tubing; and a computer-operated data-logging system that sequentially switches the transducer connection to each of the implants (and to the atmosphere) and measures and records the pressure data for each location. The pressure data consist of time-series measurements of barometric pressure at the landfill surface and subsurface pressures at implants located in the refuse or, if necessary, in native soils below and to the side of the landfill. Measurements of atmospheric and subsurface pressures are made over a period of time sufficient to include several daily atmospheric pressure maxima and minima. The typical measurement period is 2 to 5 days. Figure 2 shows a 4.8-day time series of pressure measurements taken at the landfill surface and at an implants in refuse 9.1 m and 21.3 m below land surface (bls).
These data were obtained from a lined cell covered with 0.6 m of native soil and containing 210,000 megagrams of waste collected from July, 1998 to July 2002 at a municipal landfill in Louisiana.

Analysis of Baro-pneumatic Measurements

Analysis of the field baro-pneumatic data requires a suitable mathematical model to compute gas permeabilities and the LFG generation rate. As discussed earlier, this gas flow model must be based on Darcy's law and the continuity equation. In our experience, the most useful models are site-specific three-dimensional numerical gas-flow models designed to automatically satisfy mass balance and to account for landfill geometry, cover conditions, and other realistic conditions. The

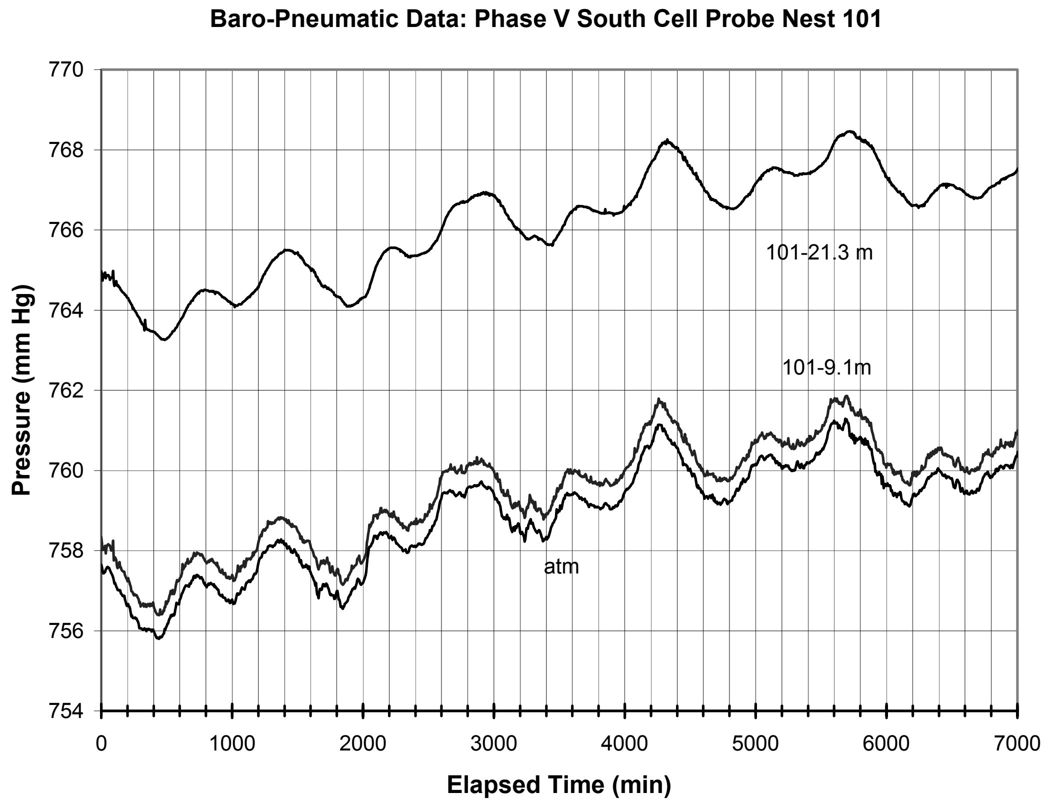


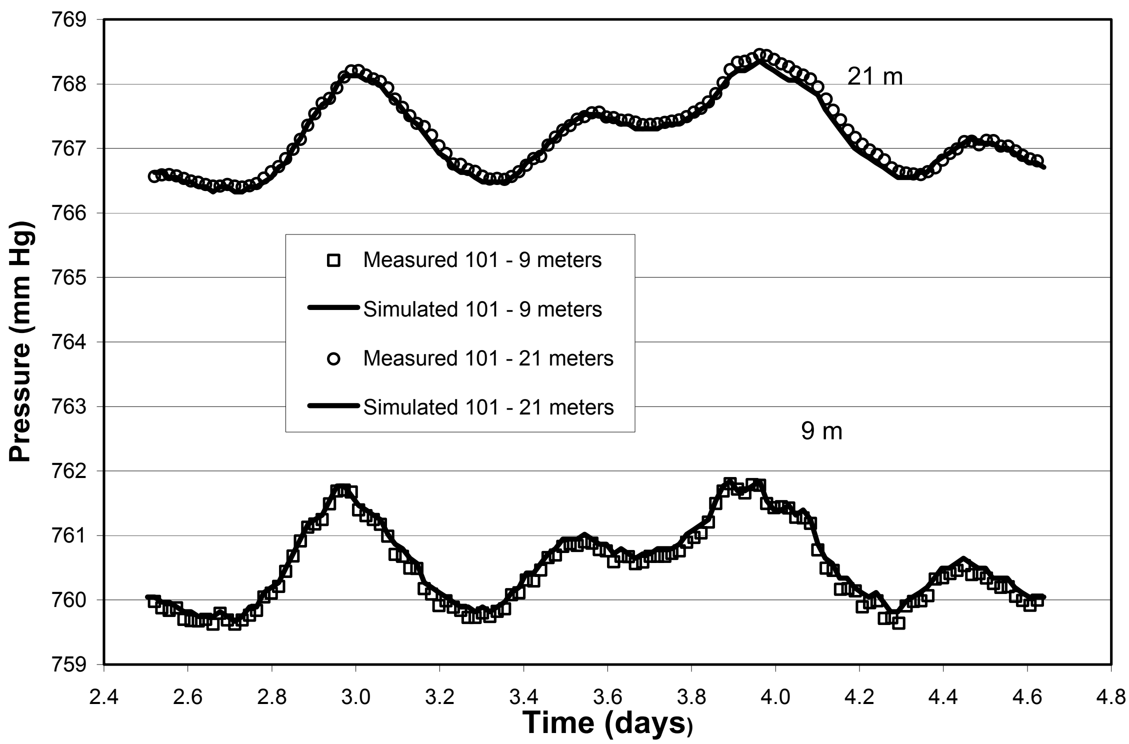
Figure 2. Baro-pneumatic data collected at 9.1 and 21.3 m bls in Louisiana MSW Landfill

model inputs include the landfill geometry and initial estimates of a landfill's (and surrounding soils') effective gas permeabilities, gas-filled porosities, and LFG generation rates. Observed barometric pressure versus time is imposed as a boundary condition on the surface of the landfill and soils. The measured pressures at the monitoring points are used to calibrate the model by adjusting LFG generation rates and effective gas permeabilities to minimize the difference between the computed and measured pressures. This adjustment process can be performed manually by trial and error or by using various automatic parameter estimation methods.

In some cases, the parameters needed for the numerical model can be derived by pressure monitoring alone. Under most landfill conditions, one or more short-term gas-extraction tests may be required to refine parameter estimates such as horizontal landfill permeability or gas-filled porosity. A typical gas-extraction test would consist of pumping a gas extraction well for one to two hours while monitoring pressure drawdown in the extraction well and one or more observation probes.

Figure 3 provides a numerical model match to the pressure data presented in Figure 2. The model was constructed using the flow and transport code TRACRN (Travis and Birdsell, 1988), a three-dimensional finite difference computer code developed at Los Alamos National Laboratories. TRACRN is capable of simulating gas and liquid flow and solute transport under conditions of variable water saturation. The match shown in Figure 3 was obtained by adjusting vertical gas permeability and landfill gas generation in a model simulation of the cell.

Figure 3 Measured and Simulated Pressures at Location 101 (Phase 5)



The landfill refuse porosity was assumed to be 40%, and the water-filled porosities of the landfill cover and surrounding soils were assumed to be 40%, yielding an effective gas porosity of 24%. The permeability of the refuse and cover material and the LFG generation rate were then adjusted until the pressures measured at depths of 9.1 and 21.3 ft bls were in reasonable agreement with simulated pressures as shown in Figure 3. The LFG generation rate obtained was 3.3 x 10^{-5} standard cubic meters per minute per cubic meter of refuse (scmm/m^3). Although this cell had a relatively high permeability cover, sufficient lag and attenuation in the signal were available to estimate both permeability of landfill refuse and cover and the LFG generation rate.

Baro-pneumatic Measurements at Other Landfills

Harrison Landfill, located in Tucson, Arizona, is an unlined, MSW landfill in Tucson, Arizona that was closed to disposal activities in 1997. The landfill covers an area of approximately 280 hectares, and is capped by a compacted, silty soil cover. The total thickness of the landfill varies from about 2 m to approximately 30 m. Total LFG generation in Harrison Landfill in 1996 was estimated to be 51 m^3/m (EMCON, 1996). The perimeter LFG collection and flare system, designed to control off-site methane migration, was expanded to a 57 m^3/min capacity extraction rate in 1998, began operating at 27 m^3/min in September 1998, and has had its rate reduced to approximately 18 m^3/min since then.

HGC conducted barometric tests at existing multi-depth soil gas sampling probes at the site. The data were used primarily to estimate the vertical permeability of the cover, refuse, and vadose soils beneath the landfill. In the course of this permeability analysis, we discovered that the data could also be used to estimate LFG generation rates. The data from a probe completed at the base of the landfill (30 m bls) and located near the center of the landfill was analyzed to estimate the Harrison Landfill LFG generation rate. The total Harrison Landfill LFG generation rate was estimated to be 26 m^3/min, an estimate that appears to be more consistent with the operating conditions of the site's LFG collection system than that provided by the first-order decay model.

El Camino del Cerro Landfill, Tucson, Arizona The El Camino del Cerro Landfill is an unlined, MSW landfill located in Tucson, Arizona that was active from 1973 to 1977. The landfill, owned by Pima County, covers an area of approximately 76 hectares, averages approximately 20 m in thickness with a maximum thickness of approximately 25 m, and has a native soil cover of varying thickness ranging from approximately 1.5 to 6 m. Materials surrounding and underlying the landfill are composed primarily of gravelly sands with occasional interbeds of silty and clayey materials. Tier 2 and Tier 3 estimates of LFG generation rates were performed in 1995 (Malcolm Pirnie, 1997). The Tier 2 estimate, obtained using the EPA Landfill Air Emissions Estimation Model (Version 1.1a) was 15 m^3/min and the Tier 3 tests, conducted in June and July 1995, yielded an estimate of 39 to 48 m^3/min. Based on these estimates, an LFG collection system was designed and installed to collect and flare 45 m^3/min of LFG. This system proved unable to maintain sufficient gas quality to continue flare operation. This proved to be true even when the collection system flow rate was reduced to 14 m^3/min. Flare operation was found to be possible only if the system was operated for 1 week out of every 6 or 7 weeks. HGC performed baro-pneumatic tests at El Camino del Cerro in 2001 to obtain a reliable estimate of the LFG generation rate. These tests were conducted using multi-depth gas sampling probes located in the south-central portion of the landfill. Pressure data from probes completed at 10 m bls and 23 m bls were used to estimate the soil cover and refuse permeabilities and the LFG generation rate of the refuse using a 3-dimensional numerical model of the landfill and surrounding native materials.

Uniform LFG generation was applied to the cells in the model representing the refuse until the best match was achieved between measured and simulated pressures. The best-match total LFG generation was 2.8 m^3/min, much less than the 14.8 m^3/min predicted by a first-order decay model or the 39-48 m^3/min obtained by the Tier 3 measurement. However, this low LFG generation rate is consistent with the performance of the installed, oversized LFG collection system.

Conclusions

The baro-pneumatic methodology for estimating LFG generation rates avoids the severe practical and theoretical limitations of the Subtitle D Tier 3 methodology, which is fundamentally flawed in so severe a fashion that its LFG estimates are only coincidentally accurate. In contrast, use of the baro-pneumatic method to meet regulatory requirements is defensible on the technical grounds that it relies on well-established and theoretically sound principles of gas-flow.

Because the baro-pneumatic method relies on site-specific field measurements, the approach is not subject to the uncertainties associated with 1^{st}-order decay predictive models due to their limited accuracy lumped parameters. Properly implemented, the baro-pneumatic measurement and analysis process can be evaluated for adherence to quality assurance standards.

Based on field examples, the baro-pneumatic method's predictions of LFG generation rates are more accurate than those relying on other methods.

The baro-pneumatic method provides the additional benefit of yielding a calibrated gas flow model of the landfill. This model can be utilized to design more efficient LFG control systems for controlling NMOC or methane emissions, controlling LFG migration, or collecting LFG for LFG-to-energy systems.

We conclude for the aforementioned reasons that the baro-pneumatic methodology is a preferable alternative for estimating LFG production to the use of empirical 1^{st}-order decay models or the Tier 3 measurement methodology described in Subtitle D.

References

EMCON. 1982. Methane Generation and Recovery From Landfills. Ann Arbor Science, Ann Arbor, Michigan.

EMCON, 1996. Harrison Landfill – Landfill Gas Remediation Plan (Revised). Prepared for the City of Tucson, 1996.

Al-Hussainy, R., H.J. Ramey, Jr., and P.B. Crawford. 1966. The Flow of Real Gases Through Porous Media. Journal of Petroleum Technology. Vol. 237:624-636.

Carslaw, H.S. and J.C. Jaeger. 1959. Conduction of Heat in Solids. Oxford University Press. Oxford, England.

Doherty, J. 1994. PEST. *Watermark Computing*, Corinda, Australia, 122 pp

Hantush, M.S. 1964. Hydraulics of Wells in Advances in Hydroscience, Volume I. V.T. Chow Ed. Academic Press, New York.

Lu, N. 1999. Time-series analysis for determining vertical air permeability in unsaturated zone. J. Geotechnical and Environmental Engineering. January. pp. 67-69.

Malcolm Pirnie. 1997. Landfill environmental Studies Program-Phase 3. El Camino del Cerro Study Area Remedial Investigation Report. Submitted to Pima County Solid Waste Management, July, 1997 by Malcolm Pirnie, Inc., One S. Church Ave., Tucson, Arizona.

Pelt, R, R.L. Bass, R.E. Hinton, C. White, A. Blackard, C. Burklin, A. Reisdorph, and S. A. Thorneloe. 1998. User's Manual Landfill Gas Emissions Model, Version 2.0. Prepared for Control Technology Center, EPA and EPA Office of Research and Development.

Rojstaczer, S. and J. Turk. 1995. Field-based determinations of air diffusivity using soil air and atmospheric pressure time series. Water Resources Research. Vol. 31:3337-3343.

Shan, C. 1995. Analytical solutions for determining vertical air permeability in unsaturated soils. Water Resources Research Vol. 31, pp 2193-2200.

SCS and Augenstein. 1997. Comparison of Models for Predicting Landfill Methane Recovery. Prepared for the Solid Waste Association of North America by SCS Engineers and D. Augenstein, March, 1997.

Travis, B.J. and H.H. Birdsell. 1988. TRACRN 1.0: A model of flow and transport in porous media for the Yucca Mountain Project. Los Alamos National Laboratories. TWS-ESS-5/10-88-08.

Walter, G.R. 2003. In press. Fatal flaws in measuring landfill gas generation rates by empirical well testing. Submitted to and accepted by Journal of the Air Waste Management Assn.

Weeks, E.P. 1978. Field determination of vertical permeability to air in the unsaturated zone. U.S. Geological Survey Professional Paper 1051.