BARO-PNEUMATIC ESTIMATION OF LANDFILL GAS GENERATION RATES AT FOUR LANDFILLS IN THE SOUTHEASTERN UNITED STATES

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ABSTRACT

The baro-pneumatic method estimates landfill gas (LFG) generation rates by analyzing pressure responses in the landfill to natural variations in atmospheric pressure. The method, based on sound gas-flow principles, uses probes to monitor the pressure distribution within a landfill. The monitoring probe pressures depend on the (time-varying) barometric pressure at the surface of the landfill; the spatially varying rates of LFG production, assumed to be static during the measuring period; and the distribution of gas permeability and gas-filled porosity of the landfill, including the refuse, underlying liner materials, overlying cover materials, and surrounding soils. As changes in barometric pressure at the landfill surface propagate downward through the landfill materials, they are attenuated and retarded with depth as a function of the pneumatic diffusivity (the ratio of gas permeability to gas porosity). The (average) subsurface gas pressures, on the other hand, depend on LFG production rates and gas permeability of the landfill, in accordance with Darcy's Law. The method is typically supported by additional data regarding the porosities and horizontal permeabilities of the landfill acquired via pneumatic well tests. The LFG generation rate and the gas permeabilities of the refuse, soils, and cover materials can be estimated by calibrating a numerical simulation of LFG flow using baro-pneumatic and pneumatic test well data. This paper discusses baro-pneumatic results obtained at four municipal solid waste (MSW) landfills located in Louisiana, Tennessee, and Georgia, in the southeastern USA.

The landfills' cover and liner materials included compacted clay, low-permeability membranes, and native soils. Pressure-monitoring piezometer probes were placed at depths from 10 to 65 feet below the landfill cover(s) except at the Tennessee site, which used shut-in LFG collector wells. Baro-pneumatic data were obtained at all landfills by 4-day periods of continuous, accurate monitoring of pressures in the probes and at the landfill surface. Pneumatic tests were conducted by extracting gas from wells screened in the refuse and monitoring pressures in the extraction well and nearby probes. The baro-pneumatic testing revealed internal LFG pressures ranging from near atmospheric to as high as 140 cm of water. Some of the probes yielded uninterpretable data because they were implanted in very-low permeability materials.

Interpretation of the baro-pneumatic test data was done by constructing and calibrating one- and three-dimensional numerical gas flow models to estimate the LFG generation rates and the gas permeabilities of the refuse and cover. The model codes employed included two gas-flow finite difference codes, TRACRN and MODFLOW-SURFACT, and a parameter estimation code, PEST.

At each landfill the rates of LFG generation provided by the baro-pneumatic method were found to differ with location of waste deposition. The waste depositional history was coupled with these LFG rate data to develop and calibrate single-phase and dual-phase first-order decay models. The resulting methane potentials (L_o) and decay rates (k) for these landfills are consistently higher than the standard AP-42 default selections (EPA, 1997). The data are also consistent with a lag time for methane generation that is significantly less than 1 year. The LFG generation rates and calibrated LFG models obtained by the baro-pneumatic method appear to be sufficiently quantitative to guide engineering or economic decisions regarding LFG collection or control systems.

INTRODUCTION

Estimation of LFG generation rates has assumed increased emphasis in recent years owing to the growing need to quantify landfill methane as an alternative energy resource and to improve the engineering of LFG recovery and control systems to reduce greenhouse gas and non-methane organic compound (NMOC) emissions. Landfill gas emissions contribute about 11% of the total anthropogenic global methane production (Boeks et al., 1996). After carbon dioxide, methane is the second-most important anthropogenic greenhouse gas.

Estimating a landfill's gas production by either direct measurement or by estimation of waste-decay rates is inherently difficult. Direct measurement by monitoring surface emissions is a complex exercise because a landfill is large and heterogeneous, its emission rates vary with time and location, and LFG emissions are affected by near-surface microbial consumption of methane (Christopherson et al., 2000) and by changes in atmospheric pressure. Additionally, gas flow to soils underlying and surrounding the landfill is generally not accounted for in emission studies.

Direct measurements using Darcy's Law to calculate gas flow from measurements of soil cover permeabilities and pressure drop across soil cover materials (Zison, 1991), while technically correct, produce unreliable results because of uncertainties in gas permeability measurements of the soil cover and because of the heterogeneous distribution of gas permeability of the landfill's cover soils (and refuse).

Direct measurement of LFG generation rates by extraction well testing methods, such as those described in EMCON (1982) or in the Method 2E required by U.S. Environmental Protection Agency (EPA) in its Tier 3 estimation of NMOC emission (EPA, 1996), has recently been found by Walter (2003) to be fundamentally flawed and incapable of estimating LFG production.

Indirect estimates of LFG generation rates generally rest on the assumption that the gas production rates of refuse are a function of waste composition and disposal history. Estimates of LFG production are provided by 1st-order decay models based on generic, lumped-parameter estimates of decay rates (k) $[t^{-1}]$ and total methane potential (L_0) $[L^3/M]$ derived from the long-term records of LFG collection data at (data-source) landfills equipped with comprehensive monitoring systems (Augenstein and SCS, 1997; Pelt et al., 1998). However, applying decay rates and methane potentials derived from source landfill data to a target landfill is subject to error because these parameters (1) are affected by any errors in the estimated efficiency of LFG collection at the source landfills and (2) the decay rates and methane potential at both source and target landfills are a function of variations in landfilling and landfill management practices, waste disposal history, waste composition, moisture, and temperature (Morcet et al., 2002), all of which are difficult to assess. Use of generic, lumped parameters to evaluate LFG generation rates at a target landfill contradicts an axiom commonly associated with environmental evaluation, i.e., that all problems are site-specific.

The baro-pneumatic method uses pressure responses in the landfill to natural variations in atmospheric pressure to estimate (LFG) generation rates (Bentley et al., 2002; Bentley et al., 2003). The method monitors pressures for several days at the surface of the landfill, at probes implanted at varying locations and depths within the landfill and, depending on the landfill construction, in soils underlying and surrounding the landfill. Figure 1 shows a schematic cross-section of a baro-pneumatic data collection system.

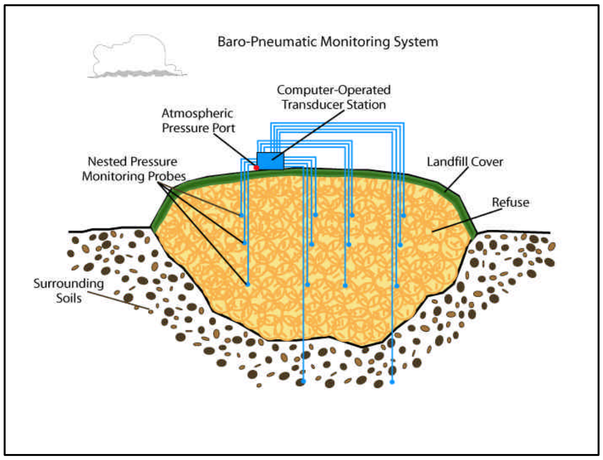

Figure 1. Cross-sectional schematic of a baro-pneumatic landfill testing system

The data collected include a continuous record of the atmospheric pressure at the surface of the landfill and the transient pressure responses in the monitoring probes resulting from the barometric pressure changes. These probe-pressure responses are delayed and attenuated as a function of depth and distribution of gas permeability and gas-filled porosity of the landfill materials (refuse, underlying soil and liner, and overlying cover). The (average) pressures within the landfill are higher than the (average) atmospheric pressure. Average refuse pressures increase with LFG production rates and decreased gas permeability in accordance with Darcy's Law. An average down-hole pressure equal to average atmospheric pressure indicates immeasurably small LFG production. The baro-pneumatic data are supported by additional, independently acquired pneumatic well test data that yield the gas porosities and horizontal permeabilities of the landfill refuse. The LFG generation rates and the gas permeabilities of the refuse, soils, and cover materials can then be estimated by calibrating a numerical simulation of LFG flow: The observed atmospheric pressure data provide a variable boundary condition, the horizontal permeabilities and porosities determined from the soil-vapor extraction (SVE) well tests (or otherwise estimated) are incorporated in the model, and the vertical permeabilities are varied to match the pressure responses observed at various depths within and beneath the landfill. Figure 2 illustrates the attenuation and lag in the pressure response relative to the atmospheric pressure. These data were obtained at a landfill in Tucson, Arizona. Note the pressure in the landfill (the dotted line) is higher than atmospheric, reflecting LFG production.

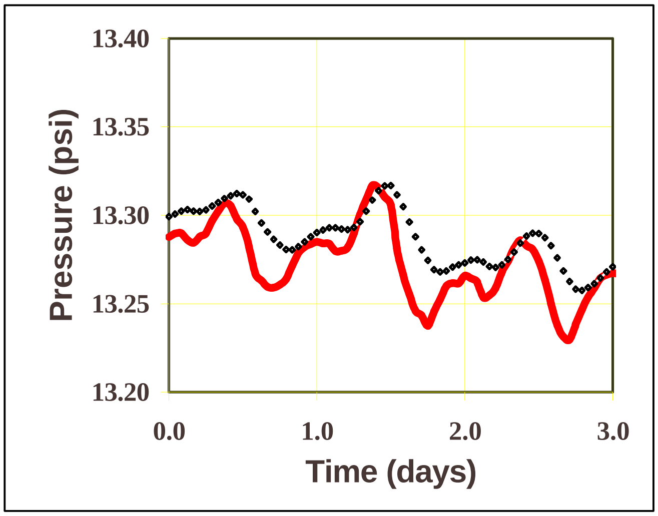

Figure 2. Atmospheric (solid line) and monitoring probe pressures (dotted line) at 100 feet below surface, Tucson Landfill

An advantage of this method is that its interpretation can be accomplished using a quantitative gas flow equation based on the well-established equations of continuity and Darcy's Law (Bentley et al., 2003). A second advantage is that the barometric response data result from pressure changes that are imposed over a large surface area (the entire landfill surface) and that traverse a large volume of landfill material between landfill surface and monitoring probe screen. The average pressure, from which the LFG estimate is calculated, is obtained from the same measurements along essentially the same flow path. For both permeability and LFG production estimates, the large scale of the measurement process tends to average out the effects of smaller-scale landfill heterogeneities. The use of the same data set for estimation of permeabilities and LFG generation should also minimize the effects of heterogeneities. This paper discusses baro-pneumatic investigations conducted at four MSW landfills located in southeastern USA.

MATERIALS AND METHODS

Baro-pneumatic tests were conducted at the St. Landry Parish Landfill located in southern Louisiana; the North Shelby Landfill, in southwestern Tennessee; the Decatur County Landfill, in southwestern Georgia; and the Houser's Mill Road Landfill, in central Georgia. Figures 3-6 are plan views of the sites showing topography and measurement locations. The waste disposal history and area, volume, and refuse mass of these landfills are summarized in Table 1.

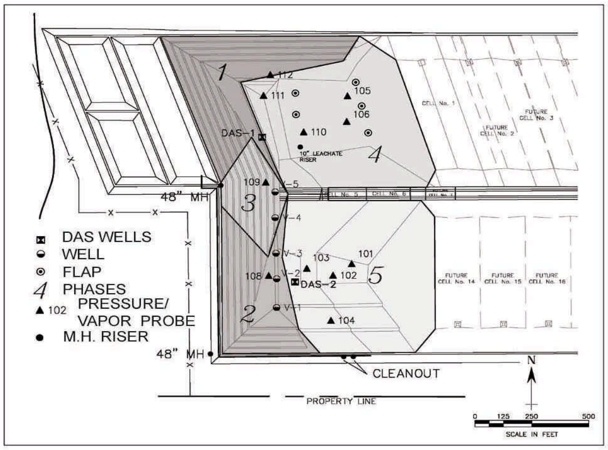

Figure 3. St. Landry Parish Landfill: plan view of cells, topography, and pressure monitoring locations

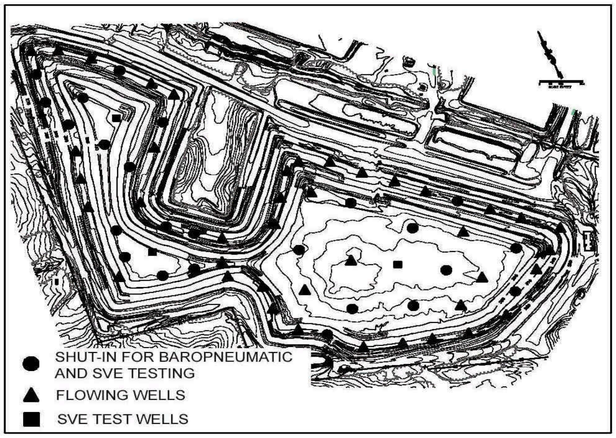

Figure 4. North Shelby Landfill: plan view including pressure-monitoring locations

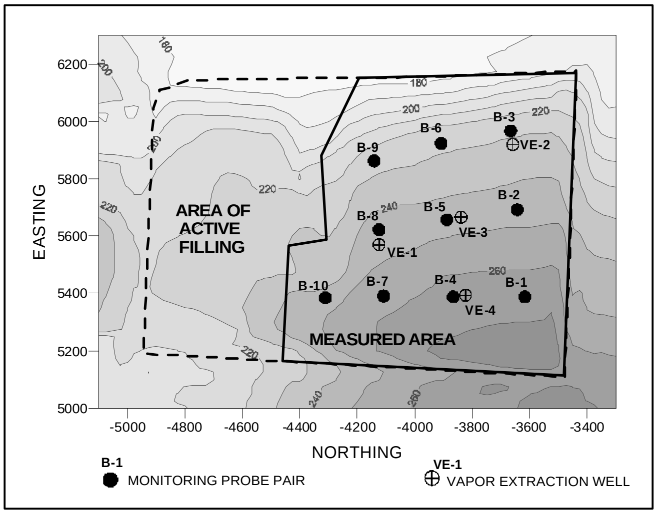

Figure 5. Decatur County Landfill: plan view, topography, and pressure probe locations

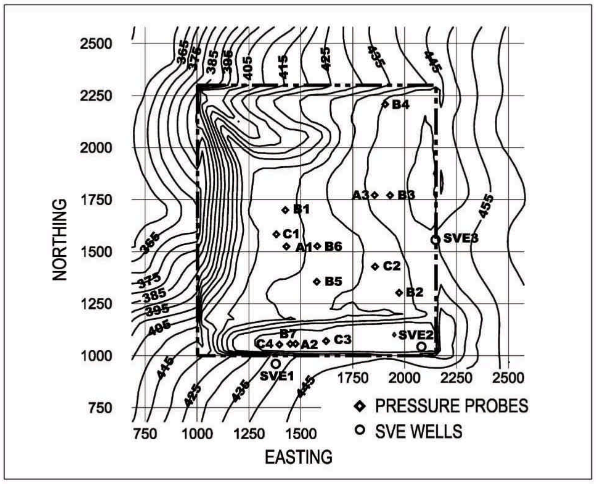

Figure 6. Houser's Mill Road Landfill: plan view, topography, and pressure- monitoring locations

TABLE 1. LANDFILLS' WASTE -DISPOSAL HISTORY, AREA, VOLUME, AND ESTIMATED MASS

	Landfill			
	St. Landry	N. Shelby	Decatur County	Houser's Mill Rd.
Year Land-filling Started	1986	1990	1982	1979
Year Land-filling Ceased (or Year of Test)	2002	1994	2004	1993
Area at Time of Test (Acres)	33	77	35	32
Current Refuse in Place (tons, estimated from volume) (x10^6)	1.06	7.76	0.973	0.725

The purpose of the testing was to estimate the pneumatic properties of the landfills, the (distributed) rate of LFG generation, and the future LFG generation. For St. Landry Parish and North Shelby Landfills, these data are intended to support LFG-to-energy projects by providing estimates of present and future methane supply and the pneumatic data to improve engineering of a LFG collection system. The objective for the Decatur and Houser's Mill Landfills was to develop a conceptual model of LFG migration and to design a collector-well LFG control system. For all the landfills, a calibrated numerical gas flow model that can be used to design the LFG collection and control system and a calibrated 1st-order decay model suitable to predict methane and LFG production were derived from the data analysis process.

The field investigations included the installation and monitoring of nested pressure probes and SVE wells at select locations within the landfills. Two or three probes were typically installed at each location to monitor pressures in shallow and deep portions of the landfill cell in order to obtain a vertical pressure distribution. In some cases, where landfill construction or other evidence suggested downward leakage, probes were placed in soils below the landfill. SVE wells were located near one or more probe nests (within 50-150 feet) to improve the prospect of obtaining useable multiple-probe SVE test data. Approximate locations of the nested pressure probes and SVE wells are shown in Figures 3-6.

Gas-Monitoring Probe and SVE Well Installation

Figures 3-6 show the approximate locations of the probes. Details of the probe placement are summarized in Table 2.

Monitoring probes at the St. Landry Parish Landfill were hydraulically implanted using a cone penetrometer rig. A 1¾-inch, hollow steel drive-point rod containing a ¾-inch, schedule 40 polyvinyl chloride (PVC) vapor probe was driven to the desired depth. A 3-foot, long pre-packed sand screen was attached to the bottom of each probe. A 1-foot long foam and bentonite donut ring was placed directly above each screen as a seal and the drive rod was retracted while the annular space was filled with 5% bentonite cement grout. No SVE wells were installed at the St. Landry Parish Landfill site.

TABLE 2. PROBE AND WELL PLACEMENT

	Landfill			
	St. Landry	N. Shelby	Decatur County	Houser's Mill Rd
No. Of Probe Locations	10	29	10	14
Total Probes	21	29	20	29
Range of Probe Depth BLS (ft)	20-76	-	5-40	4.2-40.0
Range of Screen Length (ft)	3	-	50	5-10
Deep Probes Below Refuse	0	0	0	4
SVE Wells	0	1	4	3, 3

The pressure monitoring probes and SVE wells used for the North Shelby landfill were previously installed in place collector wells associated with the site's LFG collection system. These wells were shut in one week before baro-pneumatic testing commenced. Tests at this site were conducted while LFG collection continued at the remaining, flowing wells.

The monitoring probes and SVE wells for baro-pneumatic measurements at the Decatur County Landfill site were installed by Geosciences-TTL, the main contractor at the site. A hollow-stem auger rig was used to implant probes just beneath the soil cover and just above the base of the unlined landfill. The probes were installed in a boring with an approximate diameter of 9 inches drilled to the desired depth. A 1-inch diameter, Schedule 40, flush-threaded PVC casing with a 3-foot length of 0.02 slot PVC screen at the base was then inserted into the open borehole. All casing joints were threaded and sealed with an O-ring seal. A filter pack consisting of coarse sand or pea gravel was installed to approximately 1 foot above the screens, and approximately 2 feet of bentonite chips were placed on top of the filter pack and hydrated. The remaining annular spaces were then filled to within 2 feet of the surface with on-site fine sand, and the remaining 2 feet filled with bentonite. The 4-inch SVE wells were installed with longer screens, but otherwise were similarly constructed.

Probes and SVE wells at the Houser's Mill Road Landfill site were installed by Hulsey, McCormick, & Wallace, the main contractor, using a hollow-stem auger. At each location the deepest auger hole was advanced to native soil to determine landfill depth, then screened in refuse just above the soil-refuse interface. At four locations, probes were completed in soils beneath the landfill. The probes and SVE wells were completed in a similar manner to those at the Decatur County Landfill site.

Data Acquisition Apparatus

The probes for the first three landfills were completed at the surface with gas-tight PVC valves equipped with Swagelok 1/8-inch compression fittings. These fittings were used to connect each probe to 1/8-inch polyethylene tubing. The polyethylene tubing was then used to connect each probe to one of the separate data ports on a 16-port Valco multiport valve, with one port left open for barometric pressure measurements. A digital/analog interface was used to switch the multiport valve at predetermined pressure-measurement intervals.

The data acquisition system (DAS) at the first three landfills consisted of a Setra pressure transducer accurate to 0.001 pound per square inch (psi), which was used to measure atmospheric and monitoring-probe pressures, and a laptop data logger, which switched the valve and recorded all measurements from the pressure transducer. Figure 7 shows the DAS. An advantage of using a single-transducer configuration is that sequential data from as many as 16 locations are collected at the same elevation, and the relative pressure readings required for analysis are not sensitive to low-frequency instrument drift. A disadvantage is that the hundreds of feet of tubing connecting the transducer to the pressure probe exhibit transient noise in the pressure signal, believed to be associated with windy conditions and, possibly, rapid temperature changes associated with changes in ambient solar intensity. To mitigate noise at the St. Landry Parish Landfill site, the tubing was buried in shallow trenches by landfill personnel using the corner of a bulldozer blade.

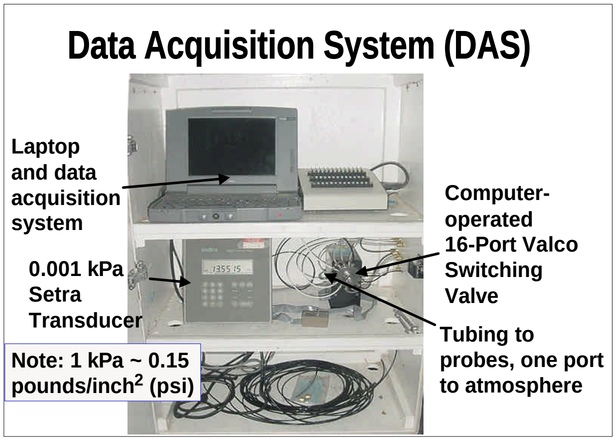

Figure 7. Single transducer-tubing DAS

Down-hole InSitu pressure transducers with automated data logging capabilities were installed at measured depths in the (¾-inch) probes used at the fourth landfill, the Houser's Mill Road Landfill. Figure 8 shows one of the downhole transducer/DAS systems. These were inserted into the pressure probes at beginning of the test. The probes were then sealed at the surface by PVC, NPT-threaded end caps equipped with a hook to hang the line to the DAS. One probe was left open and used to monitor atmospheric pressure under temperature conditions similar to the other down-hole transducers. The advantages of this transducer configuration are insulation from wind- and solar-related noise, portability of instrumentation, and reduction in field effort and costs associated with laying the tubing and protecting it from wind, sun, rodents, and vehicular traffic. A disadvantage is the potential drift of one transducer versus another and the necessity to measure the elevation of each installed transducer. Drift should periodically be monitored throughout the test to allow correction of the pressure data.

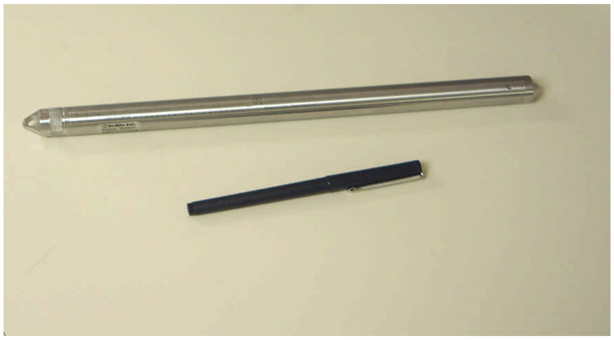

Figure 8. An InSitu down-hole transducer/DAS

A gas-tight PVC ball valve equipped with a Swagelok fitting was installed on each SVE well to allow pressure measurements to be collected by the DAS during the gas extraction well and baro-pneumatic tests.

DATA COLLECTION

Data collection consisted of the measurement of atmospheric pressure at a known elevation at the surface of the landfill and subsurface pressures in the nested pressure probes. Subsurface pressure data were also collected from SVE wells and from nearby pressure monitoring probes during transient SVE well tests.

Soil Vapor Extraction Well Testing

The SVE tests were performed using a trailer-mounted SVE unit equipped with a 200 or 300 standard cubic feet per minute (scfm) positive displacement blower. Each test consisted of pumping an SVE well and monitoring the flow rate, atmospheric pressure, and pressures in the SVE well and selected nearby gas monitoring probes. The DAS/transducer system(s) were programmed to record data at each of the various monitoring probes at 1-minute intervals. Flow rates were measured periodically by hand using a Sierra air velocity meter inserted into a 4-inch diameter pipe upstream of the blower unit bleed valve.

The usual test scenario was to pump the SVE well at three increasing levels of flow for a cumulative pumping time of approximately 1-3 hours. The recovery pressure data, collected after the SVE blower was shut down and the SVE well (immediately) shut-in, were recorded for approximately 1 to 1 ½ hours.

Baro-pneumatic Testing

Baro-pneumatic testing consisted of measuring the atmospheric pressure and the pressure within the gas monitoring probes and the SVE wells for a period of approximately 4 days. Where pressure data were collected using a multiple-probe DAS, two units were employed, each of which has the capacity for monitoring 15 probes and 1 atmospheric port. Each DAS was programmed to collect data at 5-minute intervals. The pressure reading at each location was obtained after allowing a 20-second equilibration period following the switch to that location. Pressure readings were recorded on a laptop personal computer. When the down-hole DAS/transducers were used, they were programmed to collect data at 1-minute intervals.

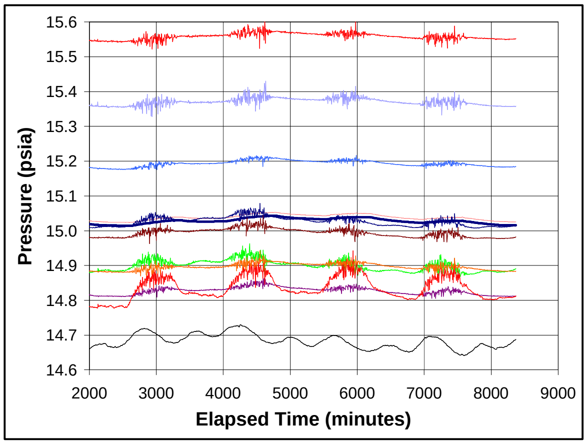

Figure 9. Monitoring data from 12 probes and an atmospheric port: west sector, Decatur County Landfill

Figures 9 and 10 compare baro-pneumatic data collected from an aboveground DAS at the Decatur County Landfill and from downhole DAS/transducers at the Houser's Mill Road Landfill, respectively. The Decatur site provided particularly noisy data because of daily wind and ongoing trash compaction.

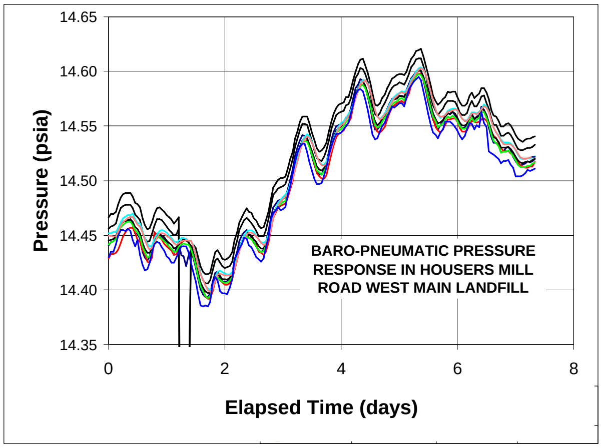

Figure 10. Baro-pneumatic data collected at seven probes and from the atmosphere, Houser's Mill Road Landfill

DATA ANALYSIS

Analysis of the test data was accomplished by constructing appropriate analytical or numerical models, and calibrating them by varying the parameters of gas permeability, gas porosity, and LFG source to provide a best fit to the test results. An analytical pneumatic well test model was used to interpret SVE well tests to provide independent estimates of landfill pneumatic properties. The baro-pneumatic data were analyzed using a numerical gas-flow model to estimate the permeability of refuse and soil cover materials, and to estimate the rate of LFG generation at various locations across the landfill. For two of the landfills, an inverse model was coupled to the numerical gas-flow model to provide automatic parameter estimation. A second analytical model was calibrated by the baro-pneumatic LFG production results to predict future LFG generation rates.

SVE Test Analysis

SVE test data were analyzed using Hydro Geo Chem, Inc.'s proprietary pneumatic test analysis computer program, ASAP, which solves the analytical solution for a leaky confined aquifer (Moench, 1985), modified for compressible gas flow. ASAP uses the measured flow rates and pressure responses as input, and solves for pneumatic properties using an automated parameter estimation routine. The well-test pressure drawdown data were corrected for changes in atmospheric pressure and then analyzed to estimate the average vertical air permeability of the cover materials and the average vertical and horizontal air permeabilities of the refuse soils. Figures 11, 12, and 13 show SVE tests conducted at, respectively, Decatur County, North Shelby, and Houser's Mill Road Landfills. Table 3 summarizes the SVE test results for each landfill. Note that porosity estimation requires data obtained from a monitoring well at known radius from the pumping well.

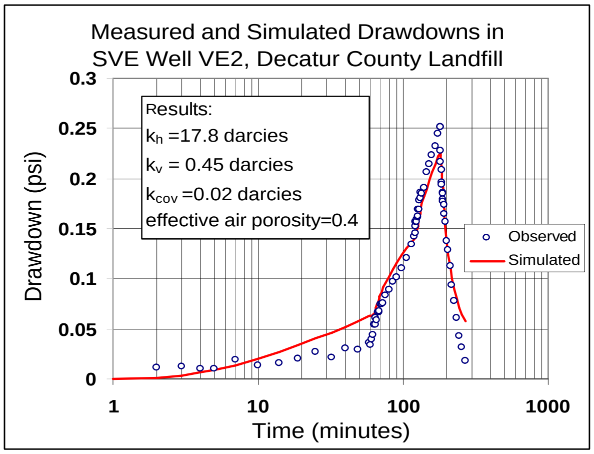

Figure 11. Pneumatic SVE test results obtained from Observation Well VE-2 at the Decatur County Landfill

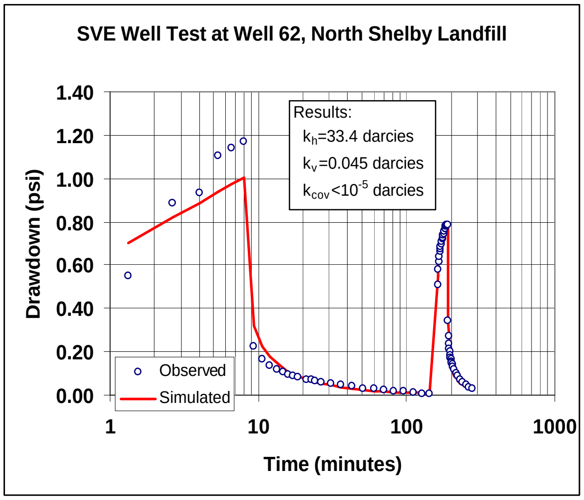

Figure 12. Pneumatic well test results from SVE Test at the North Shelby Landfill, Millington, Tennessee

TABLE 3. SVE WELL TEST DATA

Pump Well	Obs. Well	k_h	k_v	Gas Porosity	k_{cov}
North Shelby Landfill					
EW-38	EW-38	8.90E+00	1.00E-02	na	<10-5
EW-46	EW-46	1.12E+01	1.90E-01	na	<10-5
Well 62	Well 62	3.34E+01	4.50E-02	na	<10-5
Houser's Mill Road Landfill					
SVE-1	SVE-1	5.09E+01	2.82E+00	na	2.82E+00
SVE-2	SVE-2	2.85E+01	6.11E+00	na	6.11E+00
SVE-3	SVE-3	5.13E+01	3.00E-02	na	3.00E-02
A-1	C-1A	2.95E+00	2.95E-01	2.67E-01	3.72E-01
A-1	C-1B	8.60E+00	8.60E-01	7.97E-02	2.90E-04
A-2	C-4A	4.23E+01	4.23E+00	2.98E-01	4.77E-01
A-2	C-4B	4.37E+01	4.37E+00	2.97E-01	2.78E-01
A-2	C-3A	2.00E+02	2.00E+01	2.30E-01	1.86E-01
A-3	B-3B	1.04E+02	1.00E+01	8.31E-01	2.45E-01
Decatur County Landfill					
VE1	B8-A	2.10E+00	1.60E-01	3.00E-01	5.40E-03
VE1	B8-B	4.50E+01	4.50E+00	7.00E-01	1.00E-04
VE1	B7-B	1.20E+01	1.00E+00	1.80E-01	3.00E-01
VE2	B3-A	3.00E+01	2.00E-01	4.00E-01	1.00E-03
VE2	B3-B	1.78E+01	4.50E-01	4.00E-01	2.00E-02
VE2	B6-A	4.00E+01	1.00E-01	3.00E-01	1.00E-03
VE3	B5-B	2.17E+00	5.20E-01	1.00E-01	1.30E-03
VE3	B2-A	3.26E+01	3.22E+00	8.80E-02	1.0x10-4
VE4	B4-A	3.10E+00	1.00E-03	1.90E-01	1.0x10-4
VE4	B1-A	5.00E+00	7.9x10-4	2.70E-02	4.8x10-7

Notes: k_h = Horizontal gas permeability (darcies)
k_v = Vertical gas permeability (darcies)
k_{cov} = Vertical cover permeability (darcies)

Baro-pneumatic Data Analysis

Baro-pneumatic data were analyzed using a one- or three-dimensional (1D or 3D) numerical model of gas.

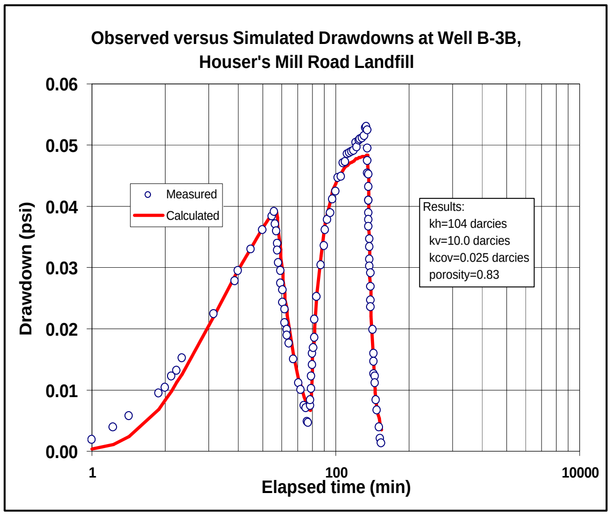

Figure 13. Results of a pneumatic SVE well test at Houser's Mill Road Landfill.

The models encompassed the landfill and surrounding and underlying vadose soils. One-dimensional simulations were considered adequate in some of the areas where significant components of lateral flow were not expected or where data were insufficient to support a fully 3-D simulation. The analyses were conducted using one of two model codes: TRACRN (Travis and Birdsell, 1988) and MODFLOW-SURFACT (Hydrogeologic, 1996), which is based on the U.S. Geological Survey finite-difference groundwater model MODFLOW (McDonald and Harbaugh, 1988). Both of these models are 3-D, finite-difference computer codes that are capable of simulating the flow of water and gas (TRACRN) or water or gas (MODFLOW-SURFACT) in variably saturated porous media.

Construction of the numerical models of the landfills consisted of a column (for 1-D simulations) or layers (for 3-D simulations) of cells of varying thickness that represented various material types. The number and thickness of the cells was based on refuse and cover thickness and lithologic soils information derived from available survey and borehole log data. These data were developed as part of the field investigation or supplied by the client. Lateral discretization in the 3-D models varied according to the geometry and waste disposal history of each site. The horizontal boundaries at the perimeter of the (3-D) models were set at 1,000 or more feet away from the landfill boundary to preclude boundary effects, or, in the case of lined landfills, the boundary of the landfill was represented as a no-flow boundary, there being no need to simulate flow in surrounding native soils. Measured atmospheric pressures were imposed at the upper boundaries (landfill surface) of the models. Zones below a water table were assigned both zero porosity and air permeability (no gas flow occurs).

Trial pneumatic parameters of gas permeability and gas porosity for refuse, cover, and soils were obtained from the results of the SVE tests or were estimated from soil properties or from results of previous landfill investigations. In the case of the St. Landry Parish Landfill, SVE tests were not performed and no direct measurement of porosity was made. At this site, anomalously low porosities were implied by discovery of high gas pressures at depth in older refuse, poor or no baro-pneumatic pressure response in most of the deeper probes, and leachate discharge from a number of deep probes when they were opened. The initial estimate of gas porosity for site refuse (24%) was therefore modified based on the assumption that settling and porosity reduction were directly related.

For each model, initial pressures were assigned to each layer in accordance with vertical interpolation of measured pressures at the start of the test. Gas pressures rapidly stabilize due to gas's low viscosity. Therefore, the initial estimated pressure only impacts the first few time steps of the simulation, and the models are relatively insensitive to the chosen initial pressure distribution.

A gas generation source term was specified within each of the landfills' model cells to simulate gas generation within the landfill waste. The initial gas generation rates were estimated according to the age of the waste, which in turn was estimated from landfill records of waste disposal and topographic maps generated at various times in the landfills' history.

Model Calibration

Calibration of the models consisted of varying the permeability of cover and refuse materials and the LFG generation rate until an acceptable match between measured and simulated subsurface pressures at specified time steps was obtained. The time steps used in the simulations ranged from 1 to 60 minutes; total time simulated ranged from 3-6 days.

For the 1-D simulations and some of the smaller 3-D simulations, the calibration was accomplished manually. For the more extensive 3-D models, the calibration was assisted using the model parameter estimation program PEST, a software application created by Watermark Numerical Computing. PEST varies model input parameters to obtain the best possible fit between the computed and measured pressure head data. The best fit to the data is defined as the minimum sum of the squares of the residuals (differences between model predicted pressure heads and measured pressure heads). This sum is referred to as the objective function. This process is essentially identical to a least-squares fitting of a line to data in a graph. Since the relationship between model input parameters and computed pressure heads is non-linear, PEST uses a Marquardt-Lambda search procedure to iteratively determine the objective function minimum. Details of this approach are presented in Bevington (1969).

The model calibration was conducted in two stages. First, the model was calibrated to the observed baro-pneumatic pressure fluctuation, ignoring the effects of gas generation. For a 1-D model, this process involved finding the best match with an LFG source set at zero. For automatic calibration, the average pressure at each probe was first compared to the average atmospheric pressure during the test measurement period. The difference (pressure head offset), which was calculated for each measurement probe, is attributable to the effects of gas generation. The pressure head offset for a probe was subtracted from each data point for that probe to obtain a data set corrected for the effects of gas generation. The model was then run to obtain a best fit to the baro-pneumatic pressure fluctuations. Our experience shows, as expected, that the model fit is most sensitive to the vertical permeability and is relatively insensitive to the horizontal permeability. In general, baro-pneumatic data are believed to provide better estimates of the vertical permeability than the SVE test results, whereas SVE test results yield better estimates of horizontal permeability.

In the second stage of model calibration, the LFG sources assigned to the model cells or material zones were varied to match the total measured pressure (combination of baro-pneumatic pressure fluctuations and static LFG gas pressure). Some iteration between the 1st and 2nd stages of model calibration was generally required to refine the calibration process. Representative results of the model calibrations are shown in Figures 14 to 19.

Figure 14 shows the results of calibrating a 3-D TRACRN model of Cell 5, the most recently completed cell at the St. Landry Parish Landfill. The dots on the graph are the measured pressure data, and the lines are the results of the simulations. The probes were implanted at 30 and 45 feet below land surface (ft bls), the higher pressure occurring, as expected, in the deeper probes. This cell received waste from 01/1998 to 07/2002, and the test was conducted in 08/2002. The methane production rate for this cell was estimated at 2.5E-5 scfm per cubic foot (ft^3) of waste in place. A third probe placed at 75 ft bls at this location, beneath an intervening geomembrane liner, showed no lag time, attenuation, or pressure offset relative to the barometric pressure fluctuations. Further evaluation revealed that the lower surface of the intervening liner was ribbed to conduct water (and, therefore, gas), and that the liner was anchored at the surface in a gravel-filled trench covered with shallow soil. We concluded that this liner was acting as an LFG conduit to the atmosphere and that this situation would need to be addressed in the design of an LFG collection system.

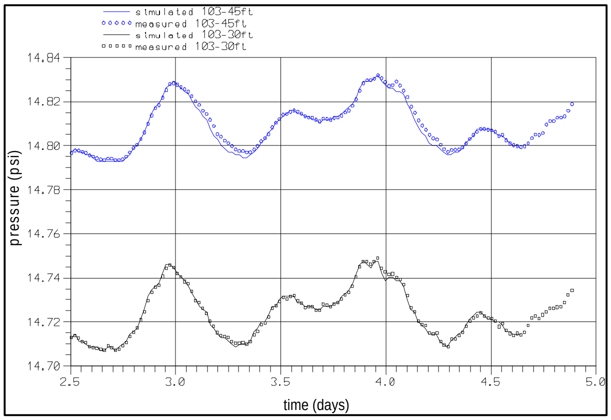

Figure 14. Measured and simulated pressures in a shallow and deep probe completed in Cell 5, St. Landry Parish Landfill

A 1-D TRACRN-model analysis of pressure data obtained from a shallow and deep probe implanted at 20 and 50 ft bls at location 105 in Cell 4, is shown in Figure 15. This cell received waste 11/1993-01/1998.

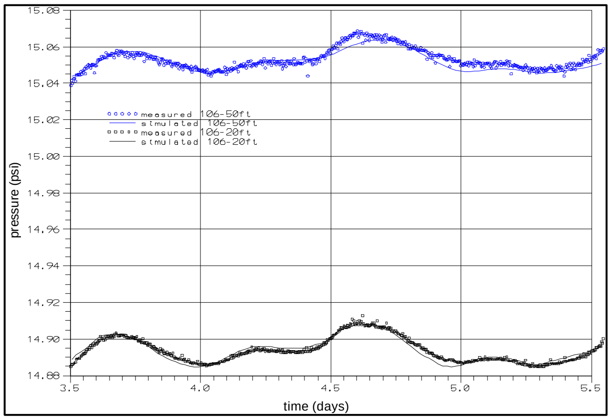

Figure 15. Measured and simulated pressures in a shallow and deep probe nest completed in Cell 4 of the St. Landry Parish Landfill

Measured and 1-D simulated pressures at the shut-in collector well EW-42 at the North Shelby Landfill are shown in Figure 16. The waste in this area was deposited from 10/1988 to 4/1990, an average residence time in the landfill of 15.0 years before the date of testing. The simulation shown in the figure resulted in an LFG generation rate of 1.12×10^{-5} scfm/ft^3 refuse at this well's location.

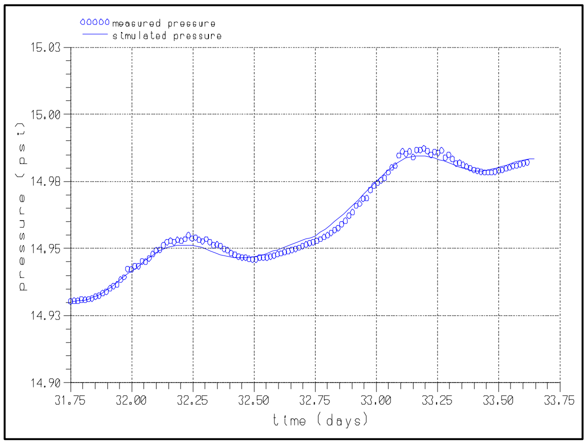

Figure 16. Measured and simulated pressures at well EW-42 during baro-pneumatic tests, North Shelby Landfill

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Figure 17 shows the measured and simulated pressures resulting from baro-pneumatic testing and 1-D TRACRN simulation at monitoring probe B-3 located in the unlined Decatur County Landfill. The figure was chosen to show the effect of tubing-related noise in the data. An unusual trend in the pressure data collected at this site was that pressures are lower in most of the deeper probes, indicating a downward pressure gradient.

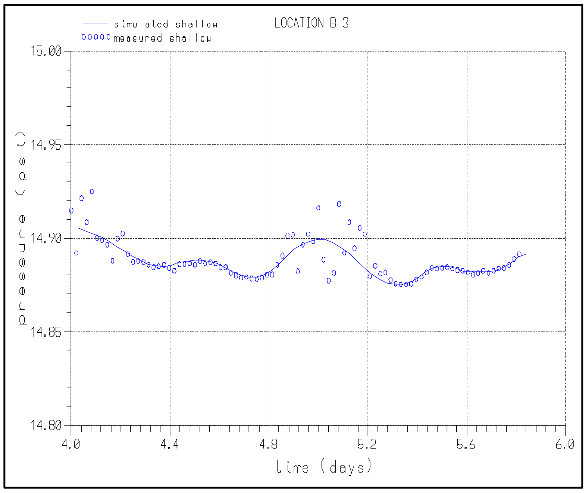

Figure 17. Measured and simulated pressures at Location B-3, Decatur County Landfill

The simulation results predict that approximately 2/3 of the LFG in the tested portion of the unlined landfill is moving downward to underlying soils and approximately 1/3 is escaping through cover soils to the atmosphere. This observation is clearly important to the objective of the test, which is to design a collector system to control LFG migration to soils. It also illustrates the value of site-specific investigation (and quantitative interpretation) to the development of critical insights as to how a landfill is interacting with its surroundings.

A second, 3-D, simulation of the Decatur County Landfill baro-pneumatic data was conducted to provide a model appropriate for designing a gas collection system to mitigate LFG migration. MODFLOW-SURFACT and PEST were the codes employed. The estimated LFG generation rates and pneumatic properties of the waste and cover soil that had been developed in the 1-D simulations were input into the 3-D model. This model was recalibrated against the baro-pneumatic data and then used to develop, optimize, and evaluate the conceptual LFG collection system design. The landfill and surrounding area were represented in the model as nine horizontal layers divided into 26 columns and 21 rows. This model was calibrated using 2,976 pressure measurements collected at 24 observation points over 5.8 days at 60-minute intervals. The calibration match is displayed in Figure 18, a plot of measured vs. simulated data.

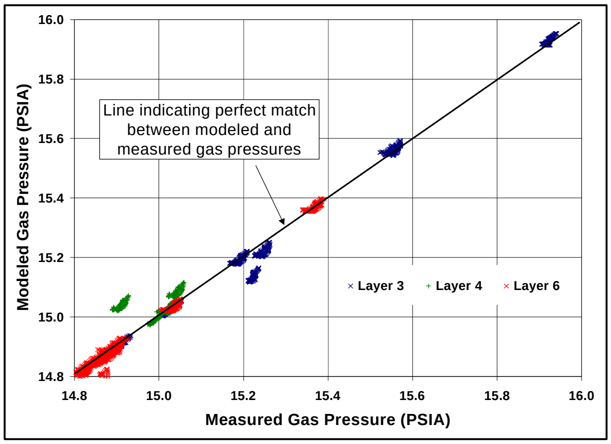

Figure 18. Measured vs simulated gas pressure for 3-D model calibration, Decatur County Landfill

MODFLOW-SURFACT was also the code employed to model LFG generation at the Houser's Mill Road Landfill. This model was supported by the parameter-estimation code PEST. The modeled area measured 3,150 feet from east to west and 3,300 feet from north to south. The 1,150- by 1,300-foot landfill was centered in the model area. The model was constructed from 9 horizontal layers divided into a 43 by 46 column area. Descending from the top, the layers included the atmospheric boundary layer, the soil cover, three landfill layers and three underlying soil layers. The 3-D simulation of the baro-pneumatic pressure data collected at this site was able to provide a good match to the baro-pneumatic data at each of the monitoring points. The match of one of the baro-pneumatic traces is shown in Figure 19.

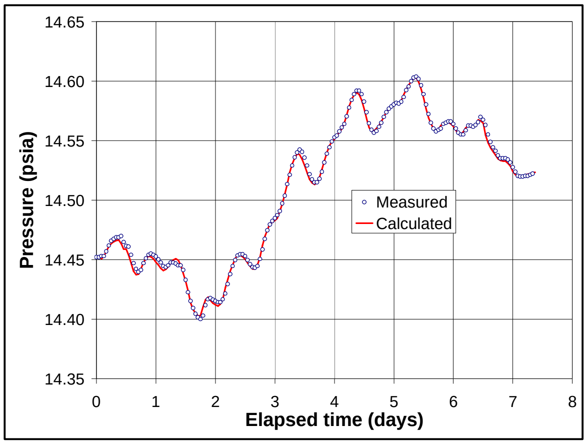

Figure 19. Measured vs. simulated pressures at probe B-6A, Houser's Mill Road Landfill

The model calibration process, described earlier, initially corrects for LFG generation effects by subtracting out pressure effects associated with LFG sources. This first-stage calibration process resulted in the plot of measured vs. simulated pressure response data shown in Figure 20. The observed calibration match is excellent. The results of the second stage calibration process, where the model is allowed to manipulate LFG source terms in each refuse layer zone, thereby providing a best-fit match to uncorrected baro-pneumatic pressure data, are shown in Figure 21.

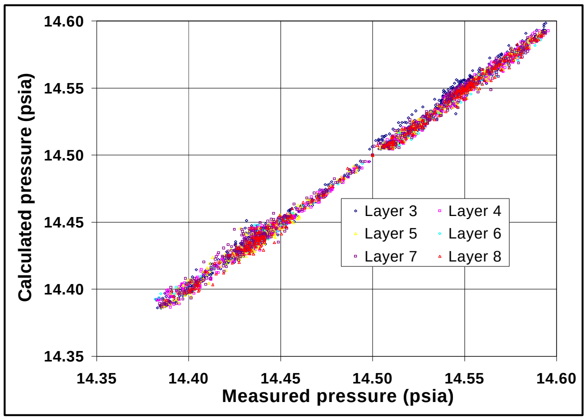

Figure 20. Stage 1 numerical model calibration of Houser's Mill Road Landfill pressures

The match of the second stage data, although good, exhibits more scatter than the first-stage match. For a number of points, the measured vs. simulated sets of data associated with some of the individual monitoring points appear to be sub-parallel to the ideal-fit line, but uniformly slightly higher or slightly lower. One possibility for this behavior is that there were small errors in the offset values used to normalize the responses of the downhole transducers.

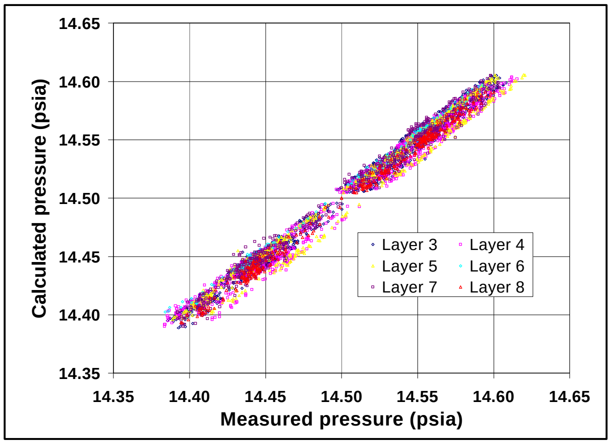

Figure 21. Stage 2 numerical model calibration of Houser's Mill Road Landfill pressures

Calibration of LFG-prediction, 1st-Order Decay Model

Predicting the future rate of LFG production was accomplished by calibrating a first-order analytical decay model using the estimated LFG production rates obtained from the baro-pneumatic tests. The models considered were a single-phase model (Pelt et al., 1998) that assumes the refuse has a single decay rate, and a two-phase analytical model (Augenstein and SCS, 1997) that considers both rapidly decomposing material such as food waste and yard trimmings, and more slowly decaying wastes such as cellulosic materials.

The 1st and 2nd model equations are, respectively:

$$LFG_{gen} = \left(\frac{1}{M}\right) L_0 R \left(e^{-kc} - e^{-kt}\right) \quad \textbf{(1)}$$

and

$$LFG_{gen} = \left(\frac{1}{M}\right) L_0 R \left[F_S\left(e^{-k_s c} - e^{-k_s t}\right) + \left(1 - F_S\right)\left(e^{-k_r c} - e^{-k_r t}\right)\right] \quad \textbf{(2)}$$

where

LFG_{gen}	is the LFG production rate of the landfill component considered (L^3/t),
M	is gas volume fraction of methane (unitless),
L_0	is potential methane produced/unit waste mass (L^3/M),
R	is the average waste acceptance rate during the active life of the landfill component (M/t),
F_S	is the mass fraction of slowly decaying waste (unitless),
k	is the rate of LFG generation per unit mass of waste (t^{-1}),
k_s	is the rate of LFG generation per unit mass of slowly decaying waste (t^{-1}),
k_r	is the rate of LFG generation per unit mass of rapidly decaying waste (t^{-1}),
t	is time since the landfill component opened, and
c	is the time since the landfill component closed.

Note that Equation 2 reduces to Equation 1 if the mass fraction of slowly decaying waste (F_S) is set to 1, i.e., if the refuse is assumed to have a single decay rate.

In order to calibrate this model, the landfill was divided into refuse components that were distinguishable by time of waste disposal. The volumes, masses, and waste disposal rates of these components were estimated from available landfill records. Volumes were estimated by using the history of waste disposal locations, topographic maps of landfill base, topographic surfaces obtained during the waste-filling history, and the current landfill surface. Waste volumes were derived from available present-day and historical topographic maps or from survey information by which topographic maps were constructed. Volumes at the time of survey were estimated by subtracting topographic surfaces. These volumes were multiplied by the assumed density (705 kilograms per cubic meter [m^3] or 44.3 pounds per ft^3), the default value recommended in Pelt et al. (1998) to obtain present-day mass. The waste mass at time of disposal was determined by dividing waste mass at time of volume measurement by (1-W_d), where W_d is the fractional waste degradation rate for times greater than 3 years, given by Equation 3:

$$W_d = 0.2 \times \left(0.176 + \log t\right) \quad \textbf{(3)}$$

Equation 3 was approximated from long-term settlement data observed for a number of landfills by Edgars et al., (1992), König et al., (1996), and Spikula (1996) (See US Army, undated).

M, the methane fraction of LFG, was derived from LFG methane measurements at the site, if available, or was assumed to be 0.50. Data regarding *R*, the average waste acceptance rate (at time of disposal), and the dates for the start and completion of waste disposal operations in a refuse area were based on information provided by landfill owners.

A least-squares objective function was used to compare LFG generation rates obtained from the baro-pneumatic tests to those obtained by Equation 1 or 2, with estimated times of disposal and waste acceptance rates for each of the refuse areas. Minimization of this non-linear function by varying the parameters common to each of the decay equations (L_o and k for equation 1 or L_o, k_s, k_r, and F_S, for equation 2), provided a best-fit estimate of methane potential, decay rate(s), and the fractions of slowly and rapidly decaying waste mass. The calibrated 1st-order decay models were then used to estimate past and future landfill LFG production.

RESULTS

Table 4 lists the best-fit parameters derived from site-specific 1st-order decay models at the four landfills discussed in this paper and from two additional landfill studies conducted by Hydro Geo Chem, Inc. in the southeastern United States. These decay models were calibrated by comparison of model prediction to baro-pneumatic LFG measurements. The table also compares the whole-landfill LFG generation rates estimated by the baro-pneumatic model to those predicted by the calibrated decay models.

TABLE 4. PARAMETERS AND PREDICTIONS OF THE CALIBRATED 1ST-ORDER DECAY MODELS (Southeastern USA Landfills)

Landfill	L_o (m^3/Mg)	F_s	k_s (yr^{-1})	k_r (yr^{-1})	Methane Gas Fraction	*LFG flow Q* (Baro-pneumatic) (ft^3/min)	*LFG flow Q* (Calibrated 1st Order Decay Model)	Time Since Close (yrs)	Refuse, tons (at time of test)
N. Shelby Memphis TN	103	1	0.078	-	0.5	1,969	1,969	10	7.76E+06
Georgia Landfill	108	1	0.086	-	0.56	142	146	10	4.75E+05
Decatur County, GA	114.9	1	0.179	-	0.5	551	551	0-6	9.73E+05
St. Landry Parish, LA	111	1	0.2	-	0.56	785	757	active	1.06E+06
Louisiana Landfill	110	1	0.238	-	0.506	7,098	7,028	active	3.74E+06
Houser's Mill Road, GA	102	1	0.148	-	0.5	510	510	12	7.26E+05
St. Landry Parish, LA (2-PHASE)	121	0.722	0.104	0.693	0.56	785	784	active	1.06E+06
Mean	108.15		0.155						
% Standard Deviation	4.56		41.1						

Reference to Table 4 shows methane potentials (L_0) varying from 102 to 114.9 m^3/metric ton (m^3/Mg), (1.63 to 1.84 ft^3/lb) with an mean of 108 m^3/Mg (1.73 ft^3/lb) and a standard deviation of 4.9 m^3/Mg (0.078 ft^3/lb), about 4.5 % of the mean. This value for methane potential is 8% higher than the AP-42 default value of 100 m^3/Mg (1.60 ft^3/lb) suggested by Pelt et al., (1998). The decay rates k, (or k_s) estimated by the baro-pneumatic process, on the other hand, are significantly greater, by factors of 2 to 6, than the 0.04 yr^{-1} suggested by Pelt et al., (1998).

In regards to the parameter estimates for methane potential (L_o) derived from the baro-pneumatic measurements, the closeness of the fit to accepted values and the small standard deviation of the data support the validity of using the baro-pneumatic method to estimate LFG generation rates and, by extension, to develop site-specific predictive decay models and provide calibrated flow models to design efficient LFG control or collection systems.

Conversely, the decay rates determined for these landfills are significantly greater than the EPA AP-42 default rate of 0.04 recommended by Pelt et al., (1998). The disparity in estimated rates might be an indication of some as-yet unidentified problem with the baro-pneumatic technique or, more likely, an indication that generic model estimates of decay rates (which ignore site specific factors) can be significantly in error. We are aware of a number of examples of LFG generation rates obtained by monitoring LFG collection systems that are as much as an order of magnitude higher, or lower, than those predicted by 1st-order decay models using default (EPA) parameters or proprietary parameters provided by landfill engineering firms.

Design Applications

To illustrate some of the applications of baro-pneumatic studies, we briefly discuss the incorporation of baro-pneumatic data (and decay-model predictions) obtained at Decatur County and North Shelby Landfills into LFG collection and control system design.

The objective of estimating LFG generation at the North Shelby Landfill in Millington, Tennessee was to assess the current and future methane that could be supplied by the landfill cells equipped with collectors and by additional cells being added to the LFG collection system. The (single-phase) calibrated 1st-order decay equation developed for that site was applied to the new areas as well and predicted a current LFG generation rate of 4,160 scfm. Expansion of the LFG system was completed and brought on-line in mid-January, 2005. According to BFI, the site's operator, the expanded collection system is now collecting 3,400 scfm of LFG (BFI, personal communication, 2005). The recoverable rate of LFG, assumed to be 75% of the total LFG generated, was predicted to be 3,120 scfm by the calibrated 1st-order decay model. The model using the default EPA AP-42 parameters predicted a much lower flow of 2,140 scfm, as shown in Figure 22.

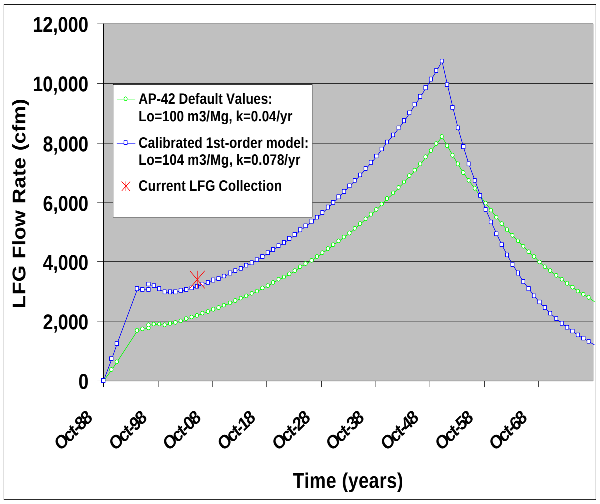

Figure 22. Comparison of recoverable LFG (assuming 75% total LFG) predicted by calibrated and AP-42 parameter models for the North Shelby Landfill

The objective of estimating LFG generation at the Decatur County unlined landfill in Bainbridge, GA was to design a landfill gas control system, using collector wells, to prevent LFG and methane migration to off-site soils. The rectangular-grid model was constructed in nine layers (the three lowermost representing native soils) 26 columns, and 21 rows. Soil, refuse (including LFG generation rates), and cover properties input to the model were estimated by the baro-pneumatic process. Wells were positioned in the model to satisfy the following criteria: 1) Prevent off-site migration of methane via soils beneath the landfill; 2) Maintain high concentrations of methane within the capture wells, and 3) Prevent the intrusion of air into the landfill that might cause ignition of the refuse. The optimized well locations for the southeastern, inactive part of the landfill are shown on Figure 23.

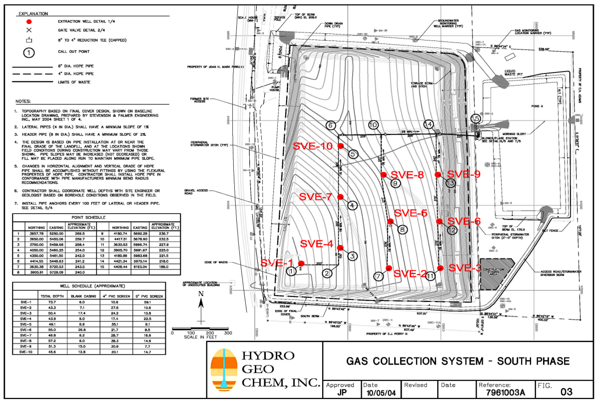

Figure 23. Collector well locations for engineering design of an LFG collection system, Decatur County Landfill

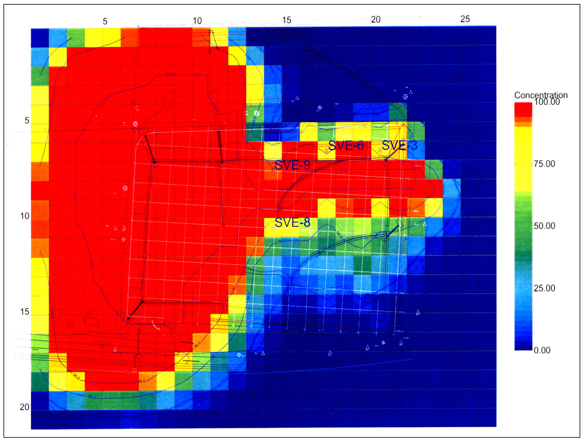

Figure 24. Simulated steady-state soil LFG distribution in the vicinity of the Decatur County Landfill equipped with the LFG control system shown in Figure. 23 (Note: north direction in this figure is to the left)

Figure 24 shows the simulated steady-state distribution of LFG in the middle layer of soils below the landfill, in model Layer 8. Note that the LFG in the southern part of the site (south is to the right in this figure) is kept close to the landfill boundary, while LFG in the uncontrolled northern part of the site occupies a significant area outside the landfill. A simulation-based design of an LFG collection and control system for this northern portion has also been completed. This expansion will be installed at an appropriate stage of the landfilling that is now ongoing at the northern part of the site.

CONCLUSIONS

The baro-pneumatic methodology shows great promise for direct measurement of LFG generation rates in landfills. It provides a quantitative estimation of LFG generation and of the landfill site's gas permeability distribution. Supported by pneumatic tests to assess gas porosity and horizontal gas permeabilities, the interpretive phase of the method provides a numerical model suitable for developing (and optimizing) conceptual engineering designs of LFG collection and control systems.

The LFG generation rates determined by the baro-pneumatic method can be used to develop and calibrate single- or multi-phase decay models that appear to offer more accurate predictions of LFG production than the non-site-specific models currently utilized by the landfill industry. The accuracy of these calibrated models is a function of not only the accuracy of the baro-pneumatic predictions, but also the accuracy of estimates of waste mass, volume, and disposal history. Accurate records and periodic surveys are as important to constructing calibrated decay models as to constructing non-site-specific decay models.

The investigation and interpretation associated with the baro-pneumatic method provides significant, additional insights in regards to the engineering design process. Every one of the known 15 applications[1] of the method to a landfill project revealed useful conceptualization and design considerations that otherwise would not have been considered. Some examples include the discovery of "hot spots" that produced anomalously high amounts of LFG; high pressures and very low permeability at depth, indicating that this landfill should not install collector wells to these depths; conduits associated with landfill construction or unusual soil conditions that are major escape routes for LFG; and downward pressure gradients indicating that the majority of generated LFG is being conducted to subsurface soils.

RECOMMENDATIONS

The consistency of baro-pneumatic results with available confirmatory data at the landfills considered in this paper, and at a number of other landfills, supports the validity of the method. Future performance of the LFG collection and control system designs based on the method will provide additional checks of its applicability. However, we believe that conducting careful, scientific tests of the baro-pneumatic method would be of significant merit. Success of such tests will accelerate acceptance of the method by the landfill industry, overcome regulatory inertia, and allow the potential energy–related and environmental benefits of a validated baro-pneumatic technique to be more quickly realized. We therefore recommend that any questions regarding the baro-pneumatic method be addressed and resolved by scientific testing of LFG rate prediction methods at one or more adequately monitored landfill sites.

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[1] Two of these landfills were non-gas generating, hazardous-waste landfills.

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