# SYSTEMATIC DESIGN OF METHANE MIGRATION CONTROL SYSTEMS

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## ABSTRACT

This paper presents a systematic methodology for design of landfill methane migration control systems. The key to the methodology is that it tests for deficiencies in the conceptual model (working hypothesis) of methane migration, correcting potential design flaws in the landfill methane control system before commencing design and construction. The testing is accomplished by (1) a field investigation of gas well extraction tests and monitoring of transient and steady-state pressures and methane concentrations in the landfill and surrounding soils; (2) constructing a site-specific numerical model of the landfill gas flow and transport consistent with the conceptual model's structure and pneumatic properties, and (3) calibrating the numerical model by modifying landfill gas (LFG) generation rates and model properties within reasonable limits to provide a best fit to the field data. Insights developed during both the field investigation and the calibration process allow identification and correction of deficiencies in the conceptual model, and, ultimately, in the conceptual engineering design. The gas flow numerical model resulting from the calibration process is used to simulate the performance of a methane migration control system and optimize the control system's performance and costs.

This improved approach is illustrated by methane control system projects recently conducted at three unlined landfills. These landfills include the City of Cairo 6th Avenue Municipal Solid Waste Landfill, located in Grady County, Georgia, the Buckhead Mesa Municipal Solid Waste Landfill, located near Payson in Gila County, Arizona, and the Decatur County SR309 Municipal Solid Waste Landfill, located in Bainbridge, Georgia. Each site investigation included a review of landfill construction and waste disposal history, installing and/or utilizing selected boreholes as gas monitoring wells or gas extraction wells, monitoring the wells' and probes' gas pressures and methane concentrations, and conducting tests to determine pneumatic parameters. Vertical and horizontal gas permeabilities were obtained by gas well extraction tests or, where estimates of LFG generation were needed, by a combination of gas pressure monitoring and gas well extraction tests. These pneumatic data were interpreted using analytical and numerical models. The resulting calibrated three-dimensional numerical gas flow and transport models were then used to develop and optimize conceptual engineering designs of methane control systems and assess their performance in meeting methane control objectives.

## INTRODUCTION

The design of a landfill-methane migration control system is done by a sequential trial-and-error approach that includes developing a conceptual model of the affected site's methane (LFG) flow system; installing monitoring wells to delineate the methane problem; designing, constructing and operating a methane control system composed of LFG control wells, trenches, or subsurface barriers; monitoring methane to determine effectiveness of these remedial control measures; modifying the control system to correct for insufficiencies in methane control; repeating methane monitoring to determine effectiveness of modified control methods; and so on. The problems with this approach are its reliance on a conceptual model that is untested and, therefore, nearly always deficient in some significant way; the rounds of monitoring and system modification required to correct the design of the methane control system; and the consequent delays and extra costs involved in accomplishing the desired level of methane control.

Identifying and correcting flaws in the conceptual model and conceptual design before commencing full engineering design and construction will eliminate costly rounds of monitoring and redesign, as will be described in this paper. Testing of the conceptual model of methane migration is accomplished by

(1) A field investigation comprised of installing monitoring probes and soil vapor extraction (SVE) wells in the landfill and surrounding soils, monitoring transient and steady-state pressures, and performing soil vapor extraction (SVE) well tests.

(2) Constructing a site-specific gas flow-and-transport, numerical mo-del of the landfill that represents its structure and pneumatic proper-

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ties. This model is a numerical representation of the conceptual model of the site.

(3) Calibrating the numerical model by modifying landfill gas (LFG) generation rates and other conceptual model properties within reasonable limits to provide a best fit to the field data.

Insights developed during the calibration process (and during the field investigation) allow deficiencies in the conceptual model to be identified and corrected.

The gas-flow numerical model resulting from the calibration process is then used to simulate the performance of a methane migration control system and compare the effects of various design modifications on control efficiency. Thus the calibrated numerical model is the ideal engineering tool to design the methane control system and maximize its cost effectiveness.

The remainder of this paper illustrates the utility of the design procedure outlined above using three case studies where the procedure was applied to landfills for the purpose of methane migration control.

**<u>Case Studies</u>**

The three methane migration control projects described herein include the City of Cairo Municipal Solid Waste Landfill, located in Grady County, Georgia, the Buckhead Mesa Municipal Solid Waste Landfill, located near Payson in Gila County, Arizona, and the Decatur County Landfill, located near Bainbridge in southwestern Georgia. These projects were selected to demonstrate the application of the methodology to the design of 3 common types of methane migration control systems: (1) extraction wells constructed in soils surrounding the landfill; (2) a gas interception trench positioned at the landfill perimeter; and (3) extraction wells installed directly in the landfill refuse. Figures 1-3 are plan views of the respective sites, showing their topography, landfill area, and pressure-monitoring probe and SVE well locations. The waste disposal history and area, volume, and refuse mass of these landfills are summarized in Table 1.

## MATERIALS AND METHODS

**<u>Well and Probe Construction</u>**

For the City of Cairo and Decatur County sites, a hollow-stem auger rig was used to drill boreholes and install the monitoring probes and SVE wells. Monitoring probes were implanted just beneath the soil cover and just above the base of the unlined landfills. The probes were installed in a boring with an approximate diameter of 23 cm (9 in) drilled to the desired depth. Flush-threaded 2.54-cm (1-in) diameter PVC casing with a 90 cm length of 0.5 mm 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 30 cm (1 ft) above the screens, and approximately 60 cm (2 ft) of bentonite chips were placed on top of the

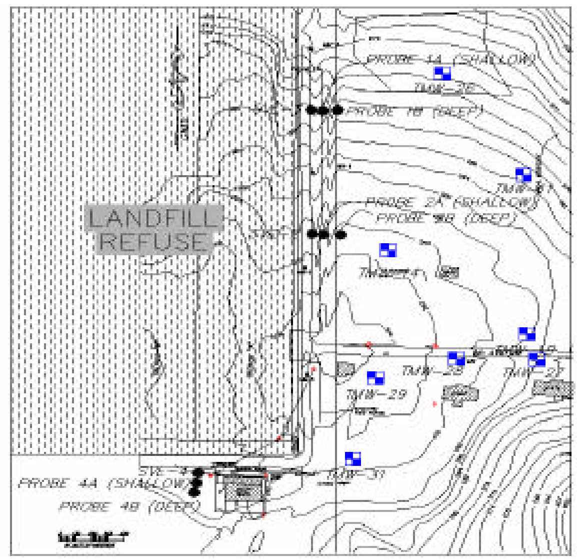


Figure 1. Plan View of the City of Cairo Landfill, SVE Wells and Monitoring Probes

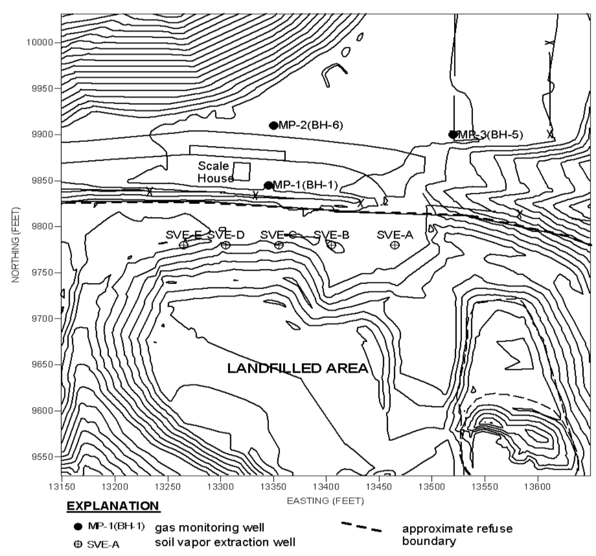


Figure 2. Plan View of the Buckhead Mesa Landfill, SVE Wells and Monitoring Probes

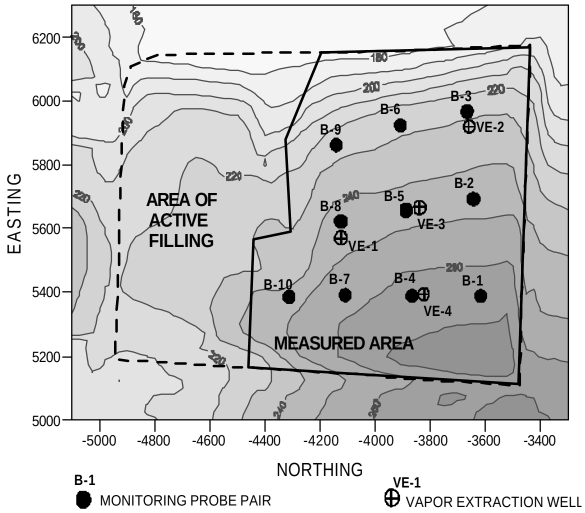


Figure 3. Plan View of the Decatur County Landfill, SVE Wells, and Monitoring Probes

| TABLE 1. LANDFILLS' WASTE -DISPOSAL HISTORY, AREA, VOLUME, AND ESTIMATED MASS | | | | | |
|---|---|---|---|---|---|
| LANDFILL | Year Landfilling Started | Year of Test | Area (Hectares) | Volume ($m^3$) | Refuse in Place (tonnes x $10^6$) |
| **City of Cairo** | 1978 | 2005 | 20.2 | -- | -- |
| **Buckhead Mesa** | 1989 | 2005 | 77 | 0.92 | 0.65 |
| **Decatur County** | 1982 | 2004 | 4 | 0.29 | 0.64 |

filter pack and hydrated. The remaining annular spaces were then filled to within 60 cm of the surface with fine sand collected on site. The remaining 60 cm was filled with bentonite. The SVE wells were 10 cm (4 in) diameter and installed with longer screens, but otherwise constructed in a similar manner.

The gas-monitoring and SVE wells used at the Buckhead Mesa Landfill site had been installed prior to the investigation (see Figure 2). The wells included five 10 cm (4 in) diameter passive vent wells completed in refuse to a depth of approximately 4.5 m. These were used as both SVE and pressure-monitoring wells. An additional three 2.5 cm (1 in) diameter gas monitoring wells were already installed. These were located in soils north of the landfilled area and screened from 1.8 to 3.6 m below land surface (BLS). Table 2 lists the probe and well placement information.

At all three sites the wells and monitoring probes were completed at the surface with gas-tight polyvinyl chloride (PVC) valves equipped with Swagelok 1/8-in (3.2 mm) compression fittings. Polyethylene tubing connected probes to the data acquisition system (DAS).

| TABLE 2. PROBE AND WELL PLACEMENT | | | | | |
|---|---|---|---|---|---|
| LANDFILL | No. Of Probe Locations | Total Probes | Range of Probe Depth BLS (m) | Probe Screen Length (m) | SVE Wells |
| **City of Cairo** | 6 | 12 | 2.4-7.6 | 1 | 3 |
| **Buckhead Mesa** | 8 | 8 | 3.7-4.8 | 1.8-4.5 | 5 |
| **Decatur County** | 10 | 20 | 1.5-12 | 1.5 | 4 |

**Data Acquisition Apparatus**

The DAS consisted of a single Setra pressure transducer sensitive to $10^{-3}$ kilopascals (kPa) [1 $\times 10^{-4}$ pounds per square inch (psi)], and a laptop data logger used to switch the valve to separate data ports on a 16-port Valco multiport valve and to record all measurements from the pressure transducer. These ports were connected to the polyethylene tubing leading from the wells and probes, with one port left open to the atmosphere for measurement of barometric pressure. The DAS switched the multiport valve at predetermined pressure-measurement intervals, typically 1 minute. Figure 4 shows the DAS.

The single-transducer configuration has the advantage that pressure 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 meters of tubing connecting the transducer to the pressure probe lead to transient noise in the pressure signal. This noise is believed to be associated with windy conditions, possibly rapid temperature changes produced by changes in ambient solar intensity, and the vibrations associated with working an active landfill face. The noise observed during several landfill site investigations has not yet proved significant enough to interfere with data interpretation.

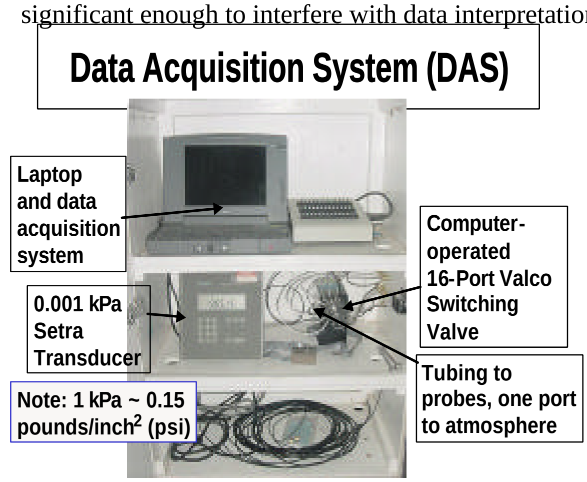


Figure 4. Single transducer DAS

**Pneumatic Testing**
The pneumatic testing conducted at these sites consisted of monitoring of atmospheric pressures, measuring pressures in gas-monitoring wells and probes in order to establish ambient pressure conditions; and monitoring selected gas monitoring wells and probes while conducting soil vapor extraction (SVE) tests.

**SVE tests** were monitored before, during, and after pumping of the SVE wells. Pre-SVE test monitoring was to establish background pressures, but primarily to measure horizontal subsurface pressure gradients induced by LFG generation. Monitoring during and after pumping was done to capture both the pressure drawdown and recovery data. The SVE wells were pumped using a trailer-mounted SVE system equipped with a positive displacement vacuum blower capable of pumping 8400 standard liters/min (slm) [300 standard cubic feet per minute (scfm)] at the Georgia sites and 14,000 slm (500 scfm) at Buckhead Mesa. The SVE well was pumped at three increasing levels of flow for a cumulative pumping time ranging from 1 to 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 1½ hours. Extraction rates were monitored periodically by a handheld flow meter. Subsurface and atmospheric pressures were continuously monitored at 1-minute intervals throughout the SVE tests.

**Baro-pneumatic testing** was conducted at the Decatur County site to estimate LFG generation rates (see Bentley et al, 2005 for additional details). 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. Each DAS was programmed to collect data at 5-minute intervals. The pressure readings at each location were obtained after allowing a 20-second equilibration period following the switch to that location. Pressure readings were recorded on the laptop personal computer.

## DATA ANALYSIS
Analysis of the test data was accomplished by constructing appropriate analytical or numerical models, described in following sections, and calibrating them by varying the distributed parameters of gas permeability, gas porosity, and, for numerical models, the LFG source to provide a best fit to the test results. An analytical model was used to interpret SVE well tests. A numerical gas-flow model was used to estimate the permeability of refuse and soil cover material, and to estimate the rate of LFG generation at various locations across the landfill. For the Decatur County site these LFG generation rates were combined with the landfill's waste disposal history to calibrate an analytical 1st-order decay model (Augenstein and SCS, 1997). This last exercise resulted in site-specific estimates of decay rate and methane potential that were utilized 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 SVE test pressure drawdown data were corrected for changes in atmospheric pressure and then analyzed to estimate the average vertical and horizontal air permeabilities of the refuse or soils interrogated by the SVE well and monitoring probes; the average vertical air permeability of the cover materials or confining bed(s), and the average gas porosity. Note that porosity estimation requires data obtained from a monitoring well at known radius from the pumping well.

Figures 5, 6, and 7 show the data and analysis of representative SVE tests conducted at the City of Cairo MSW Landfill, the Buckhead Mesa MSW Landfill, and the Decatur County MSW Landfill. The x-axes in these figures are the times since the SVE pump was turned on. Drawdown at a selected time is the difference between the pressure at the start of the test and the observed pressure at the selected time.

The sharp drop in drawdown at late time is the decrease in pressure resulting from shutting down the pumping well. Table 3 summarizes the SVE test results obtained for each landfill. Gas permeabilities are listed in darcies (1 darcy ~ $1 \times 10^{-12}$ m$^2$).

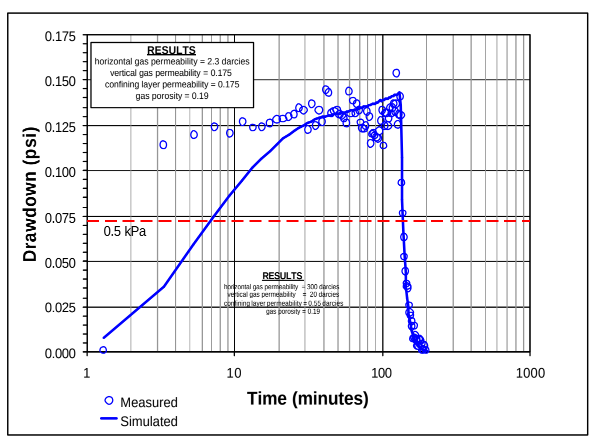


Figure 5. Measured & simulated drawdown in 2A while pumping SVE-2, City of Cairo MSW Landfill

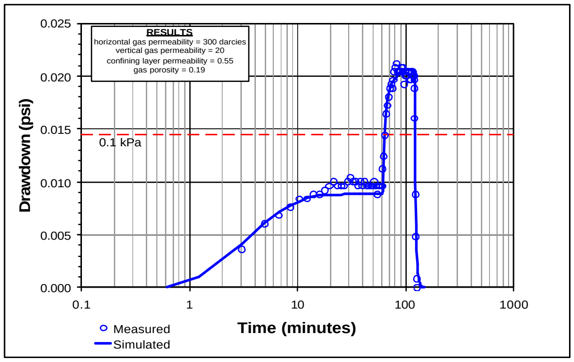


Figure 6. Measured & simulated draw-down in SVE-E during pumping of SVE-A; Buckhead Mesa MSW Landfill

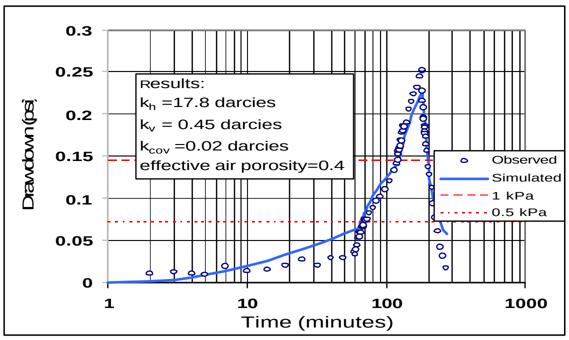


Figure 7. Measured & simulated draw-down in B8A during pumping of VE1, Decatur County MSW Landfill SR309

## NUMERICAL MODELING

Two numerical model codes were employed. TRACRN (Travis and Birdsell, 1988) was used for all three projects, and MODFLOW- SURFACT (Hydrogeologic, 1996) was additionally employed for the Decatur County project. Both are finite-difference computer codes that are capable of simulating 3-dimensional flow in variably saturated porous media. TRACRN simulates flow of both water and gas, and MODFLOW- SURFACT, either water or gas.

**Model Construction:** Numerical gas-flow and transport models were constructed for each site using lithologic and elevation data collected in the field or available in previous site reports. The permeability and porosity results of the SVE test analysis were incorporated into the models. The models were calibrated by varying their rates of LFG generation at various locations across the landfill to provide a best fit to the observed ambient subsurface gas pressures and gas-pressure gradients.

In the case of the baro-pneumatic tests at Decatur County Landfill, the calibration included varying both input permeabilities and LFG generation rates to match the response of landfill and soil gas pressures to transient changes in atmospheric pressure at the landfill surface. The baro-pneumatic model calibration was assisted using the model parameter estimation program PEST (Doherty, 1994). PEST uses a Marquardt- Lambda search procedure to iteratively determine the best fit to the computed and measured pressure data. Details of this approach are presented in Bevington (1969).

**Material Types and Distribution:** The material types represented in the models included various soils, refuse, cover material and "air". "Air" indicates a model volume where the land surface is below the upper model boundary elevation. "Air" was represented in the models as a material with an LFG concentration of zero, a very high permeability of 10,000-50,000 darcies, and a very high gas diffusion coefficient of 1 × $10^4$ $m^2$/sec. Materials below the water table were assigned a gas saturation of 0.00.

Table 4 shows the pneumatic properties of the materials represented in the site models. Initial values of permeabilities were obtained from SVE tests for Cairo and Buckhead Mesa and from baro-pneumatic tests conducted at Decatur County (discussed later). The distribution of site materials was determined based on borehole logs or other relevant information such as observed or inferred high or low permeability, water levels in monitoring wells, etc.

**TABLE 4. Pneumatic Properties Represented in the Numerical Model**

| Material | $k_h$ (darcies) | $k_v$ (darcies) | Total Porosity | Water Saturation | Gas Porosity |
|---|---|---|---|---|---|
| **City of Cairo Municipal Solid Waste Landfill** | | | | | |
| sand | 5.7 | 0.57 | 0.4 | 0.7 | 0.12 |
| clayey sand | 1.5 | 0.015-0.15 | 0.4 | 0.7 | 0.12 |
| refuse | 50 | 5 | 0.4 | 0.5 | 0.20 |
| cover | 0.1-0.15 | 0.05-0.15 | 0.4 | 0.7 | 0.12 |
| "air" | 10,000 | 10,000 | 0.4 | 0.1 | 0.81 |
| **Buckhead Mesa Municipal Solid Waste Landfill** | | | | | |
| soil | 5 | 5.0 | 0.23 | 0.2 | 0.18 |
| refuse | 220 | 20 | 0.19 | 0.2 | 0.15 |
| cover | 1 | 0.65 | 0.19 | 0.2 | 0.15 |
| "air" | 10,000 | 10,000 | 0.90 | 0.1 | 0.8 |
| trench | 1,000 | 1,000 | 0.90 | 0.1 | 0.8 |
| **Decatur County Municipal Solid Waste Landfill** | | | | | |
| native soils | 5.4 | 0.036 | 0.0054 | 0.3 | 0.3 |
| cover | 0.31 | 0.0095 | 0.36 | 0.22 | 0.28 |
| upper refuse | 0.4 | 0.031 | 0.53 | 0.21 | 0.42 |
| lower refuse | 218 | 0.55 | 0.53 | 0.21 | 0.42 |
| "air' | 50,000 | 50,000 | 0.53 | 0 | 0.53 |

***Notes:***
***$k_h$ = Horizontal gas permeability***
***$k_v$ =Vertical gas permeability***
***$k_c$ =gas permeability of confining layer ("aquitard") or cover***

## City of Cairo MSW Landfill Model

**Model Dimensions:** A plan view of the City of Cairo Landfill gas flow and transport model mesh is shown in Figure 8. The model extended 580 m in the east-west and north-south directions, the model was 18.2 m (60 ft) thick, and its base was 73.2 meters above mean sea level (amsl). The model consisted of 41 columns, 41 rows, and 18 layers. Row and column spacing were uniformly 15.2 m except near the landfill margins where spacing was reduced to 7.6 m (25 ft). Model layers were 0.76 m (2.5 ft) thick in its lower half and 1.52 m (5 ft) in its upper half. The model domain covered the southeast portion of the landfill and surrounding areas to the east, southeast, and south of the landfill

**Boundary Conditions:** The lower, north, and west boundaries were specified as no-flow, and the upper, south, and east model boundaries were assigned constant pressure and water saturations. LFG concentrations at the upper, south, and east boundaries were maintained at zero.

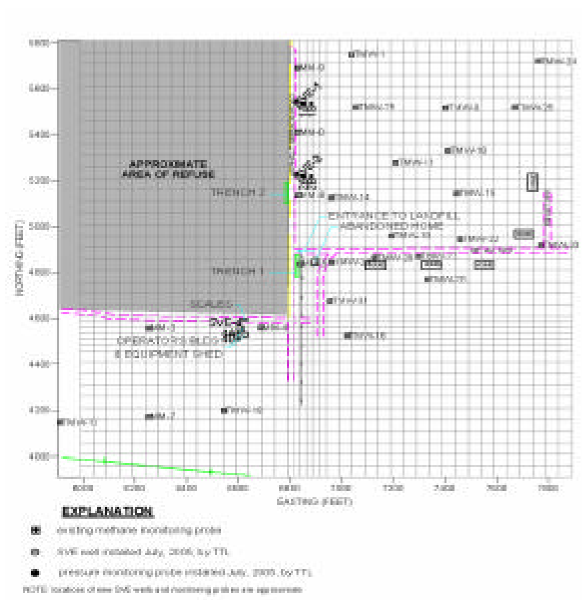


Figure 8. Site map showing numerical model domain and mesh of City of Cairo MSW Landfill.

Five material types were represented in the model: clayey sand, sand, refuse, cover material and “air”. Refuse was placed within the area shown in Figure 8 and was assumed to be covered by clayey cover materials and have a base elevation of 81 m amsl. Table 4 shows the pneumatic properties of these materials represented in the model.

The boring logs and elevation data indicated unsaturated sands ranging from 0.2 to more than 3.7 m deep extending east from the southeast portion of the landfill. The shape of this zone was found to be generally coincident with the observed area of high subsurface LFG concentrations. Clayey materials overlie this zone and likely behave as a semi-confining layer, aiding lateral migration of LFG to the east. In the model, the sands were assumed to extend beneath the landfill as shown in Figure 9.

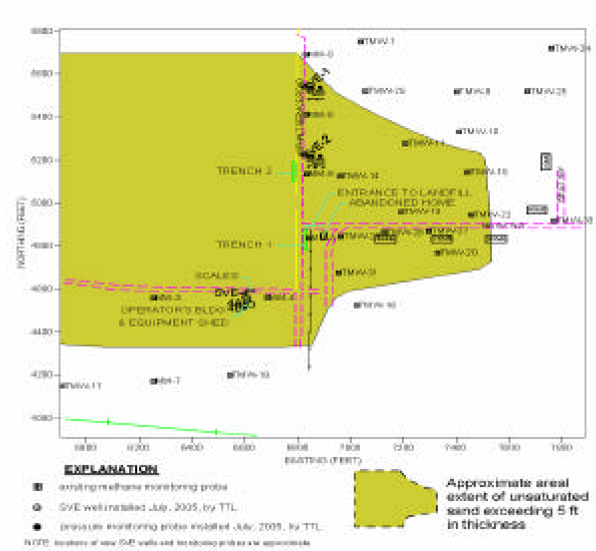


Figure 9. Approximate areal extent of sand layer exceeding 1.4 m thickness. City of Cairo MSW Landfill

The permeability and porosity of the refuse, not measured, were assigned values typical to those at similar sites, i.e., 50 and 5 darcies for horizontal and vertical gas permeabilities, respectively, and 0.20 for gas porosity.

**Model Calibration** consisted of adjusting model LFG generation rates assigned to refuse materials and permeabilities of landfill cover and vertical clayey sand in the vicinity of SVE-4 until the simulated subsurface gradients near SVE-1, SVE-2, and SVE-4 were similar to those observed in the field investigation. As a result of the calibration process, the LFG generation rate was set at 0.0129 slm/m$^3$ refuse (1.28 x 10$^{-5}$ scfm/ft$^3$ refuse), and the gas permeability of the southern portion of the cover materials was raised to 0.15 darcies.

**Simulation of Landfill Gas Migration** was performed by running the model forward in time until near steady-state conditions were attained. Simulated results for layer 10 (approximately 80 m amsl) are shown in Figure 10.

As shown, most of the LFG is predicted to migrate offsite to the east within the area where unsaturated sands occur, as shown in Figure 9. LFG concentrations above 0.1 (10%) are also predicted to occur along the southern margin of the landfill. This LFG distribution is reasonable in accordance with past measurements. The overall area of predicted impact is slightly larger in the simulations (which will result in a more conservative, therefore more protective, design).

**Design Simulation:** Simulation of LFG control systems was conducted for a number of potential designs, each incorporating the three existing SVE wells.

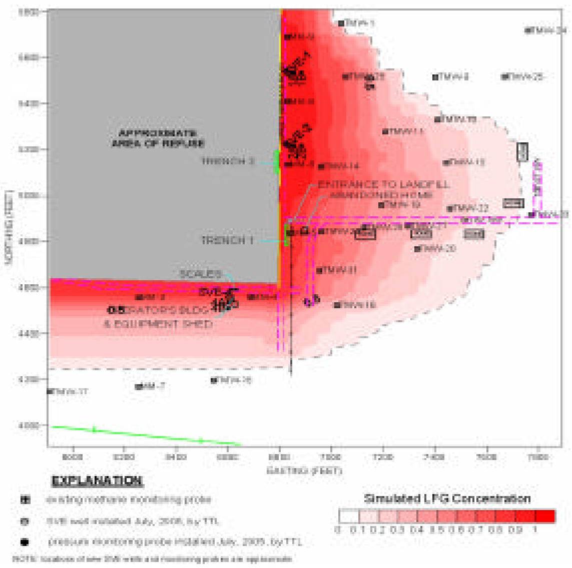


Figure 10. Simulated steady-state LFG concentrations at 80 m amsl, City of Cairo MSW Landfill

The most cost-effective design used a total of 12 perimeter SVE wells (3 existing and 9 new installations) with a total extraction rate of 2500 slm (90 scfm) and variable screened intervals and extraction rates for individual wells. The proposed locations of the 9 new wells are shown in Figure 11, which also shows the simulated steady-state LFG concentrations when the designed methane control system is operating.

As shown, the designed control system will remove subsurface LFG that has already migrated offsite to the east of the proposed SVE wells. Removal of gas from this area will take some time, perhaps a year or more. However, a short-term benefit will occur within about a month of operation as a subsurface vacuum develops. This vacuum, shown in Figure 12, will limit or prevent possible LFG movement upward into surface structures over the short term.

## Buckhead Mesa MSW Landfill Model

**Model Dimensions:** A plan view of the Buckhead Mesa Landfill gas flow and transport model mesh is shown in Figure 13. The model extended 150 m (500 ft) in the east-west and north-south directions. The

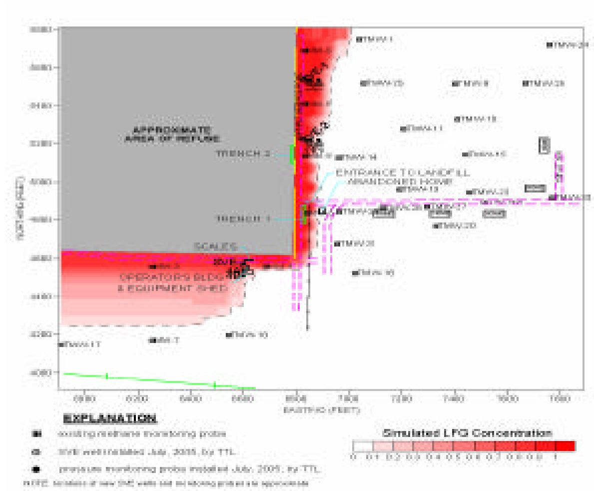


Figure 11. Proposed locations of 9 new SVE wells and simulated steady-state LFG distribution under well operation, City of Cairo MSW Landfill

model was 15.2 m (50 ft) thick, and its base was 158 meters (5180 ft) amsl. The model consisted of 25 columns, 65 rows, and 20 horizontal layers. The row spacing was 1.52 m (5 ft) near the landfill margin and 3.05 m elsewhere. The column spacing was uniformly 6.1 m (20 ft). Model layer spacing ranged from 0.7 to 2.4 m (2 to 8 ft). The model domain covered an area along the northern boundary of the landfill where offsite LFG migration was known to occur.

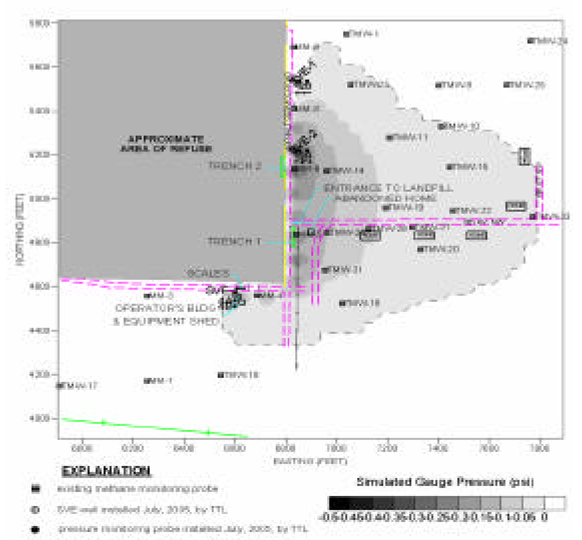


Figure 12. Simulated gage pressure at an elevation of 8.14 m bls using existing and proposed wells for control system. City of Cairo MSW

**Boundary Conditions:** The lower, southern, eastern, and western boundaries were specified as no-flow (movement of gas at these lateral boundaries is roughly parallel to the boundaries) and the upper and northern model boundaries were assigned constant pressure and water saturations. LFG concentrations at the upper and northern boundaries were maintained at zero. The northern boundary was far enough away that internal concentrations were not impacted by this condition.

**Material Types and Distribution:** Four material types were represented in the model: surrounding soils, refuse, cover material, and "air. Table 4 shows the pneumatic properties of these materials represented in the model. Refuse was assumed to be covered by silty-to-clayey sand. Materials other than "air" were assigned a lateral dispersivity of 0.3 m (1 ft) and a transverse dispersivity of 0.03 m (0.1 ft). The permeability and porosity of the refuse and cover materials were based on values estimated from the SVE tests.

**The Calibration Process** consisted of adjusting LFG generation rates assigned to refuse materials in the model until the simulated subsurface

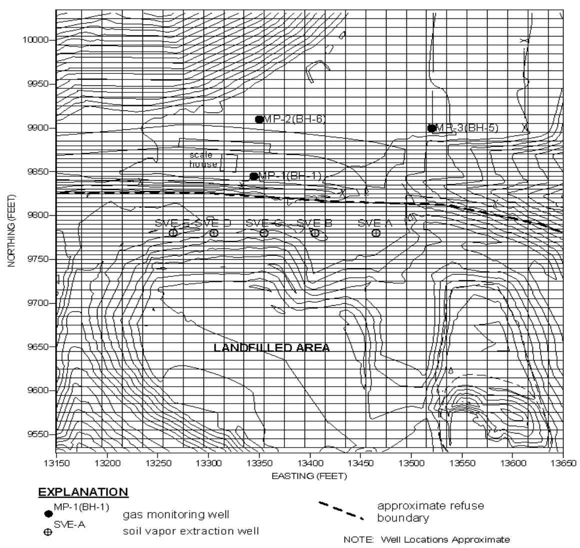


Figure 13. Site map showing numerical model domain and mesh of Buckhead Mesa MSW Landfill. .

gas pressure gradients across the landfill boundary and in soils north of the boundary were similar to those measured during the field investigation. As a result of the calibration process, the LFG generation rate was set at 0.016 slm/m3 refuse (1.6 x 10-5 scfm/ft3 refuse).

**Simulation of Landfill Gas Migration** was performed by running the model forward in time until near steady-state conditions were reached. Simulated results for layer 3 (approximately 1583 m or 5195 ft) amsl) are shown in Figure 14.

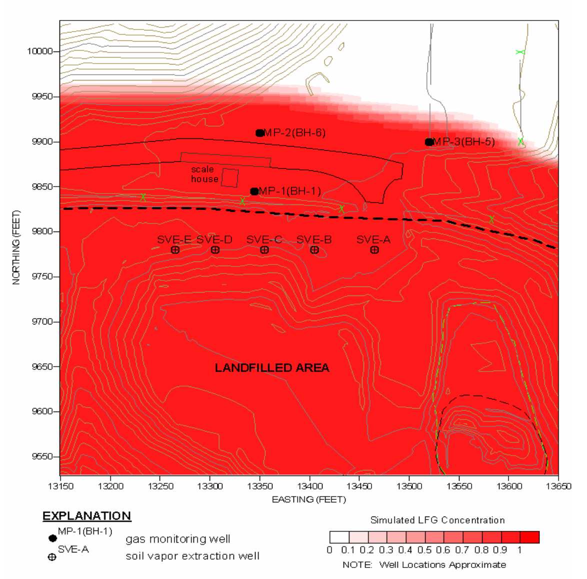


Figure 14. Simulated steady-state LFG concentrations at 1583 m amsl. Buckhead Mesa MSW Landfill

Most of the LFG is predicted to migrate off site to the north just past the locations of MP-2 (BH-6) and MP-3 (BH-5). This simulated distribution is generally reasonable based on past measurements, although the overall area of predicted impact and the predicted concentrations are slightly larger in the simulations. This was regarded as desirable from the standpoint of methane control design, as it will result in a more conservative design.

**Simulation of Potential Landfill Gas Control System** was conducted for a number of potential designs. These designs did not include active pumping of the existing vent wells as this was judged unacceptable with regard to fire risk. (The potential for air (oxygen) intrusion is high due to the relatively high vertical gas permeability estimated for the cover material based on the SVE well tests). Therefore, only perimeter systems with actively pumped components completed in soils outside the refuse were considered. Potential design choices focused on a trench system rather than wells.

The selected design consisted of a 3 m (10 ft) deep trench. Variable lengths and extraction rates were simulated to determine most effective design. The selected configuration consisted of a trench extending over the area shown in Figure 15 and pumped at 500 slm (18 scfm), or 4.6 slm/m (0.05 scfm/ft).

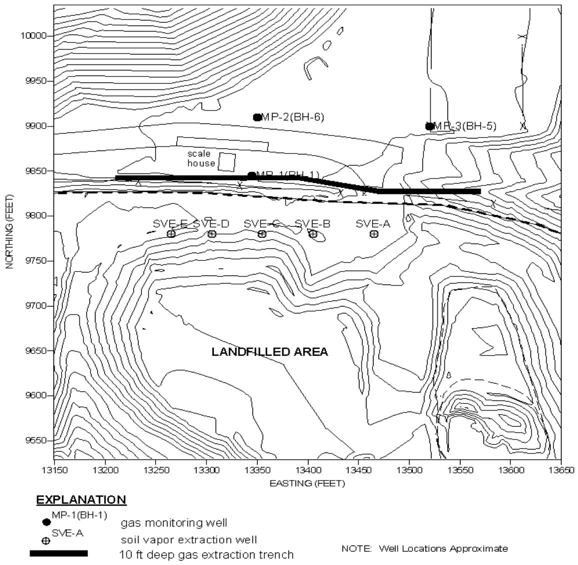


Figure 15. Location of selected methane control system vapor-extraction trench Buckhead Mesa MSW Landfill

**Decatur County MSW Landfill Model**

The primary goal at the Decatur County site was the design of a system to prevent off-site migration of hazardous concentrations of methane. A second goal was to provide compliance with the Clean Air Act (CAA) regulatory criteria for New Source Performance Standards (NSPS) regarding non-methane organ-

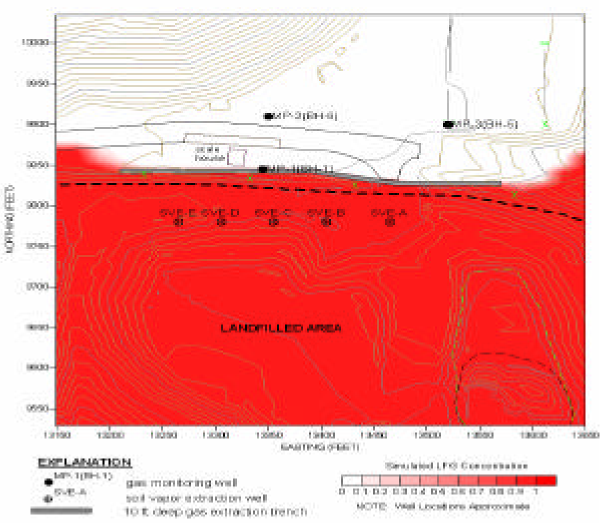


Figure 16. Simulated steady-state LFG distribution under operation of selected methane control system SVE trench, Buckhead Mesa MSW Landfill

ic compound emission controls at MSW landfills.This second goal was requested by the client, although compliance with NSPS rules was not required because the design capacity of the Decatur Landfill is less than 2.5 million tons. Meeting both of these goals requires efficient collection of LFG from the landfill, and, because of variable gas generation rates and pressures within a landfill, is a notably more difficult method of controlling methane migration than installing pneumatic barriers outside the landfill perimeter (such as those described in the two previous examples). The dual goals were addressed by conducting a baro-pneumatic investigation (Bentley et al., 2005; Bentley et al, 2003, Bentley et al, 2002) to define the distribution of LFG generation at this landfill and predict its future LFG generation. This approach, and the site-specific numerical model that was generated by the baro-pneumatic investigation, allowed the design of a control system to efficiently capture LFG for both migration and emission control.

**The Baro-pneumatic Method** involves collecting a continuous 4 or more-day record of 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 the distribution of gas permeability and gas-filled porosity of landfill refuse, underlying soil and liner materials, and overlying cover materials. The pressure signals within the landfill are higher than the atmospheric pressure signals owing to LFG generation in the landfill. Figure 17 illustrates the attenuation and lag in the pressure response relative to the atmospheric pressure at a landfill in Tucson, Arizona. Note the pressure in the landfill (the circles) is higher than atmospheric (the solid line), the difference reflecting subsurface LFG generation. Average refuse pressures increase with landfill gas generation rates and decreased gas permeability in accordance with Darcy's law.

The baro-pneumatic data are supported by independently acquired SVE well test data regarding the gas porosities and horizontal permeabilities of the landfill refuse. The LFG generation rate and the vertical gas permeabilities of the refuse, soils, and cover materials can then be estimated by calibrating a numerical gas-flow simulation of the landfill. The atmospheric pressure data are used as a landfill surface boundary condition; the horizontal permeabilities and porosities determined from the SVE well tests (or otherwise estimated) are input to the model; and the LFG generation rate and vertical permeabilities are varied to match pressure responses observed at various depths within and beneath the landfill. Figure 18 shows the observed subsurface baro-pneumatic data at probe B-3 at the Decatur Site compared to the simulated results of a calibrated 1-dimensional model. The periodic noise in the observed data is believed to be associated with waste compaction activities at the face of the working landfill.

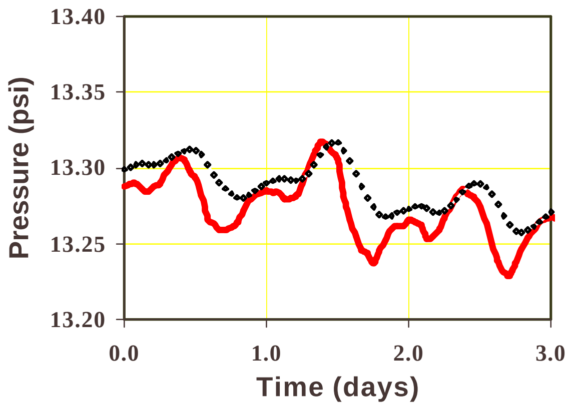


Figure 17. Atmospheric (solid line) and monitoring probe pressures (30 m below surface; Tucson, AZ Landfill)

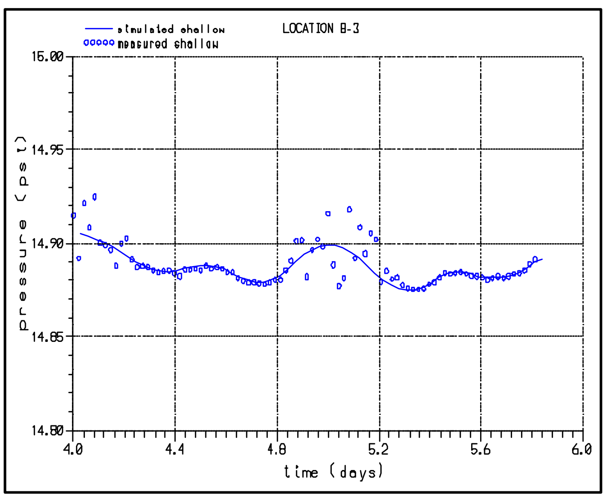


Figure 18. Observed baro-pneumatic pressure response (circles) and model-simulated pressure response at probe B-3, Decatur County MSW Landfill.

An advantage of this method is that its interpretation is 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 imposed over a large surface area (the entire landfill surface) and that traverse a large volume of landfill material between landfill surface and probe screen. For both permeability and LFG generation estimates, the large scale measurement process tends to average out the effects of smaller scale landfill heterogeneities. A third advantage is that the offset pressure, from which the LFG is estimated, is obtained from the same measurements and along the same flow path as the barometric response data.

**The Modeling Approach** was, first, to analyze the baro-pneumatic data at each probe location to determine the relatively localized LFG generation rates and vertical permeabilities at that location. Figure 18 shows one of these model analyses, conducted using the numerical code TRACRN. (One interesting attribute of the data was the observation of a downward vertical gradient in most of the probe pairs, indicative of significant methane migration to underlying and surrounding soils.)

A 3-dimensional model was then constructed (using the numerical code MODFLOW-SURFACT) and calibrated by allowing the horizontal permeability and gas generation rates to vary while holding the vertical permeability values fixed.

**Model Dimensions:** A plan view of the 3-dimensional Decatur County Landfill gas flow and transport model mesh is shown in Figure 19. The model extended 640 m (2100 ft) from east to west and 792 m (2,600 ft) from north to south. The landfill was located in the center of the model and measured approximately 427 m (1400 ft) from north to south and 275 m (900 ft) from east to west. Elevations for the top of the current landfill and for the ground surface were obtained from a topographic survey of the site, or, where not covered by the survey, east and south of the landfill were extrapolated from the topographic data and are therefore approximate. Elevation of the bottom of the refuse was interpolated from logs of borings. Groundwater

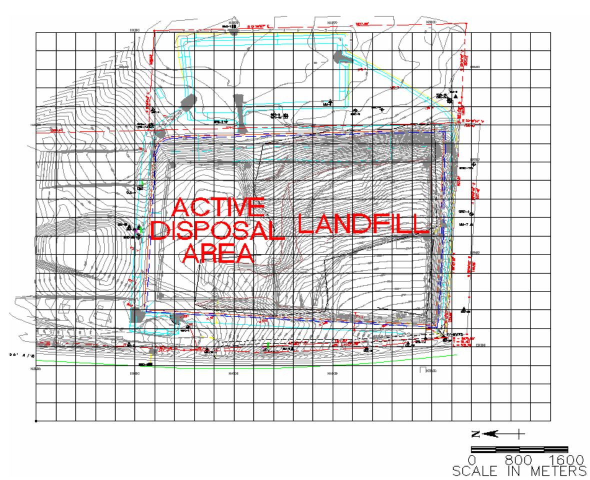


Figure 19. Site map showing numerical model domain and mesh of Decatur County MSW Landfill.

data suggest that a perched water zone exists in unconsolidated soils above a limestone bedrock layer.

The model consisted of 26 columns, 21 rows, and 9 layers. The column and row spacing was uniformly 30 m (100 ft). Model layer spacing was variable to reflect variations in the ground surface elevations, refuse and cover thicknesses, and groundwater surface elevation.

The layer descriptions are as follows:

1. Layer 1: a 30 cm layer of "air"
2. Layer 2: landfill cover and air outside the landfill (0.5-1 m)
3. Layers 3,4,5,6: 0.6-12 m refuse within landfill; 0.15 m each outside the landfill
4. Layers 7,8,9: native soils underlying the landfill

The depth to the base of the model grid (the bottom of the $9^{th}$ layer), was taken to be the distance to the perched water table.

**Boundary Conditions:** The atmospheric pressures measured during the test were assigned as the boundary condition for the layer -1 "air" layer. The lower layer boundary was assigned as no flow in accord with the existence of the zero-gas permeability water table at that depth. The lateral perimeter boundaries were set far enough away from the landfill to have no impact on LFG concentrations, and, therefore, were specified as no-flow with LFG concentrations maintained at zero.

**Material Types and Distribution:** Four material types were represented in the model: native soils, refuse, cover material, and "air". Refuse was assumed to be covered by silty to clayey cover. Table 4 shows the pneumatic properties of these materials represented in the model. Materials other than "air" were assigned a lateral dispersivity of 0.3 m (1 ft) and a transverse dispersivity of 0.03 m (0.1 ft).

The initial values of horizontal permeability of the refuse and cover materials were based on values estimated from the SVE tests. The water saturation of the refuse, hence its gas porosity, was calculated by the model from van Genuchten parameters (van Genuchten, 1980) taken from Benson and Wang (1998). The resulting water saturations varied with elevation above the perched water table.

**The Calibration Process** consisted of specifying an LFG source term within each of the landfill model cells. A total of 22 sectors was specified with different gas generation rates corresponding to each of the permeability zones in the upper and lower landfill refuse. These gas generation rates and the sector horizontal permeabilities were iteratively varied for each sector by means of the PEST automatic calibration code to adjust LFG generation rates until the simulated subsurface gas pressures were similar to those measured during the field investigation. The horizontal permeabilities obtained by this process were found to be 1 to 2 orders of magnitude higher than the vertical permeabilities, a range consistent with data obtained at other landfill sites. The model calibration yielded a good-to-excellent fit to the baro-pneumatic pressure data as shown in Figure 20. The statistics of the model fit yielded a correlation coefficient of 0.988 with a standard error of 0.29 kPa (0.0422 psi).

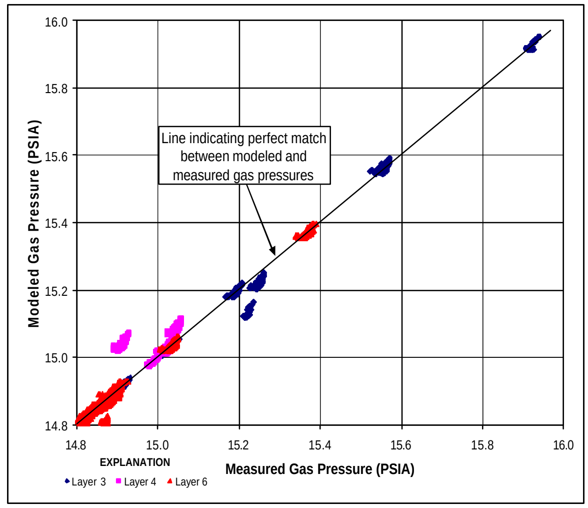


Figure 20. Comparison of observed and simulated baro-pneumatic pressure data. Decatur County MSW Landfill

A first-order decay equation calibrated to the numerical model results was used to estimate the maximum amount of LFG generated from the landfill under future waste disposal conditions. The analytical decay expression, modified from Augenstein and SCS (1997) is given by

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

Where

| | |
|---|---|
| $LFG_{gen}$ | is the LFG production rate of the landfill component considered (volume/time] |
| $M$ | is gas volume fraction of methane (unitless), |
| $L_0$ | is potential methane produced/unit waste mass (volume/mass), |
| $R$ | is the average waste acceptance rate during the active life of the landfill component (mass/time), |
| $k$ | is the rate of LFG generation per unit mass of waste ($time^{-1}$), |
| $t$ | is time since the landfill component opened |

and
*c* is time since landfill component closure

The calibrated gas decay coefficients were k = 0.179/yr and $L_0$ = 115 m3/metric ton.

As a result of the calibration process, the current (June, 2004) LFG generation rate was estimated at 21,100 slm (745 scfm). The peak generation rate of 26,200 slm (925 scfm) is estimated to occur upon facility closure in 2006. These generation rates are about 20 % higher than those obtained using the 1-dimensional model simulations, probably a result of using the higher porosities predicted from the van Genuchten equation in the 3-dimensional model. The higher results were used in the design process because they provided a conservative (more protective) LFG collection and control system.

**Simulation of Potential Landfill Gas Control System Designs** was conducted by running models equipped with operating control systems forward in time until near steady-state conditions were attained. The selected design consisted of a system of 10 extraction wells for capture of LFG (methane) from the non-active portion of the landfill to prevent off-site migration of gas from that area. Gas extraction rates, screened intervals, and well locations were adjusted to achieve containment of all subsurface methane from the inactive portion of the landfill. Figure 21 shows the plan view layout of the selected methane control system.

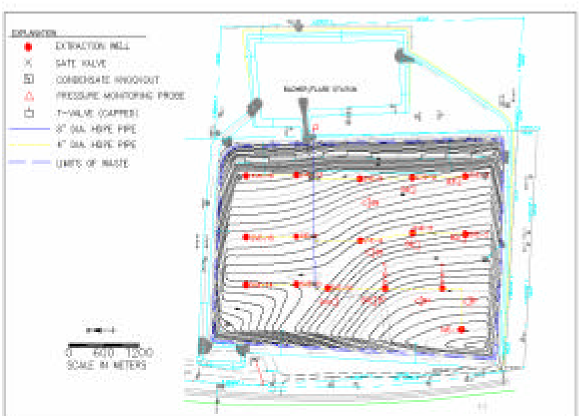

Figure 21. Layout of selected methane control system at the Decatur County MSW Landfill

The system was optimized to satisfy the following criteria:

1. Prevent off-site migration of methane through the subsurface
2. Maintain high concentrations of methane within the capture wells
3. Prevent intrusion of air that might cause waste ignition

The simulated system proved to be successful in controlling subsurface LFG migration from the closed portion of the landfill while maintaining high concentrations (95% or better) of LFG in the extraction wells. Figure 22 shows the LFG distribution in model layers 2-6 (refuse and landfill cover) resulting from operation of the extraction well system to steady state. Note that LFG migration is still occurring to the north (left side). This migration, from the uncontrolled, active sector of the landfill, will be addressed by an expanded system to be designed and installed after landfill closure in 2006.

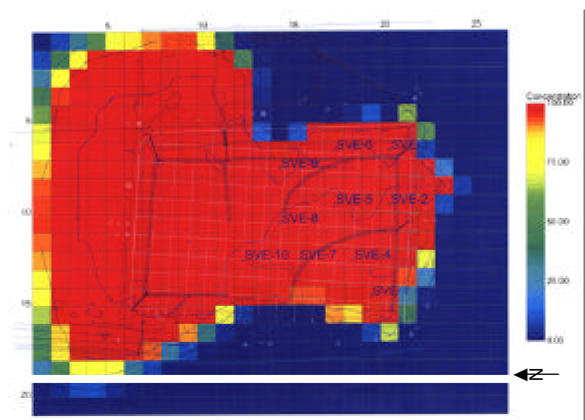

Figure 22. Simulated LFG distribution in Layer 7 after 20 years operation of selected extraction well system.

**Gas Collection System criteria:** Criteria considered in the design of the pipe network included minimization of

1. amount of piping required
2. number of elbows, valves, junctions, and other pipe fixtures
3. potential for condensation within the system
4. cost of construction

Additional criteria included provision of a relatively even distribution of vacuum and facilitation of (later) expansion into the active northern disposal area.

A Darcy-Weisbach analysis of system pressure requirements was conducted to size and locate the blower. The resulting design specifications were a minimum vacuum of 234 kPa (3.5 psi) and a flow rate of 26,000 slm (925 scfm). This flow rate will be sufficient to meet present and projected NSPS criteria.

**CURRENT STATUS OF CASE STUDY PROJECTS**

**The City of Cairo MSW** landfill methane control conceptual engineering design has now been reviewed and verbally approved by the Georgia Environmental Protection Division (GEPD), the regulatory oversight agency.) The engineering design has been prepared by TTL, Inc. The City of Cairo plans to install the system utilizing city equipment and personnel.

**The Buckhead Mesa MSW Landfill** methane control project design was completed and submitted to Arizona Dept. of Environmental Quality, the regulatory oversight agency. The conceptual engineering design specified an extraction rate of 500 slm (18 scfm). In November 2005 a venting system was installed consisting of a 75 m (250 ft) cutoff trench, located as specified in Figure 15 and equipped with a wind-driven turbine venting system. Monitoring indicated significant decreases in methane concentrations in the compliance wells. By January, 2006 methane levels had decreased in compliance wells to non-detect levels. Measured combined flow through the vent wells ranged from 550-1100 slm (20-40 scfm).

**The Decatur County MSW** methane control engineering design has been completed and reviewed and approved by GEPD. The system is currently under construction.

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