AN ANALYSIS OF LANDFILL GAS MONITORING WELL DESIGN AND CONSTRUCTION

by

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INTRODUCTION

This study was conducted by the Missouri Department of Natural Resources through a grant provided by the U.S. Environmental Protection Agency to evaluate the impacts of the Great Flood of 1993 on Missouri landfills. The purpose of this portion of the overall project was to compare the ability to accurately measure landfill gases in soil using different well construction techniques.

METHODS

Site and Well Selection

Seven landfills were selected for testing. Each site had a history of gas migration and was evaluated prior to drilling to be sure it was suitable for this study. Figure 1 shows the landfill locations. These sites were selected because of their representative geological settings and soils with respect to the state of Missouri. The locations of well sets at each landfill were determined by historic information at that landfill plus interpretation of geological and topographical information. The vertical placement of well screens was determined by inspection of the soil cores taken at the time of well placement, the depth to groundwater, and monitoring of gas in the well bore during drilling. The descriptions to follow refer to the drilling logs and cores and so do not necessarily apply to the entire landfill setting.

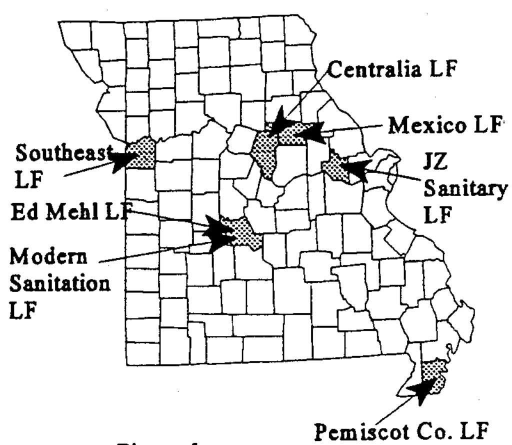

Figure 1

Description of Soils and Hydrogeology at Specific Landfills

Table 1 summarizes information about the soils and hydrogeology of each landfill, including the location, geomorphic setting, bedrock stratigraphy, general surficial materials, and stratigraphy and permeability characteristics. Aquifer data include the aquifer name, depth to the aquifer (not any perched water zone), gradients and general water quality. The data on soil stratigraphy and permeability were collected from borings at each site and are presented below:

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Geological Survey Program Hydrogeologic Data for Flood Grant Sites

Site, County, Legal Location	Geomorphic Setting	Bedrock Stratigraphy	Bedrock Permeability Characteristics (Likely fluid and gas migration zones are underlined)	Surficial Materials Stratigraphy	Surficial Materials Permeability Characteristics (Likely fluid and gas migration zones are underlined)	Aquifer Data: Aquifer Name/ Characteristics	Aquifer Data: Depth to Water	Aquifer Data: Gradients	Aquifer Data: General Water Quality
Pemiscot County Landfill Pemiscot County NE 1/4, NE 1/4, Sec. 1;- T. 18 N.;- R. 12 E. Caruthersville Quad	Southeast Missouri Lowlands (Alluvial Floodplain of the Mississippi River)	N.A.	N.A.	Alluvial Silty Clay to clayey silt over sand and gravel	Low to moderate in silty clay to clayey silt. High in sands and gravels.	Mississippi River alluvium (Excellent yield)	10 to 20 feet (est)	Normally to the east (toward Mississippi River	Excellent
Southeast SLF Jackson County N ½, NE 1/4, Sec. 22;- T. 48 N.;- R. 33 W. Grandview Quad	Floodplain of the Blue River	Pennsylvanian-aged shales and limestones of the Pleasanton Group	Low permeability in shales which underly the site. Bedrock is an aquitard.	Alluvium, silty clay to clays overlying coarser materials near the bedrock contact	Low to moderate in upper portion. Increasing to moderate to high in coarser zones at depth.	Alluvium (Unconsolidated clay, silt, sand and gravel)	3 - 20 feet	E to S	May be poor due to industrialization
						Pennsylvanian Pleasanton Group (Poor yields)	N.A.	N.A.	Poor quality. Generally high TDS
Ed Mehl SLF Camden County SE 1/4, NW 1/4, Sec. 23;- T. 39 N.;- R. 18 W. Green Bay Terrace Quad	Ozark Plateau Ridgetop	Ordovician Gasconade Dolomite (dolomite, chert and sandstone)	Flow predominantly through fractures and solution openings. Landfill is developed in one of the most karst stratigraphic intervals in the Ordovician.	2-3 feet of silty clay loess over relict chert and sandstone beds interlayered with flocculated residual clay.	Low to moderate in loess, overall high permeability in residual soils due to relict chert and sandstone beds.	Gasconade Dolomite (Fair to good yield)	100 feet (est)	N.A.	High bacteria counts but generally good chemical quality.
Modern Sanitation SLF Camden County NW 1/4, SE 1/4, NW 1/4, Sec. 33; T. 39 N.;- R. 16 W. Camdenton Quad	Dissected Ozark Plateau	Ordovician Roubidoux Formation and Gasconade Dolomite	Flow through fractures and solution openings.	Stoney clay residuum with relict chert and sandstone beds interlayered with residual clay.	Generally high through relict beds and other macropores.	Roubidoux Formation and Gasconade Dolomite (Good yield)	Approx. lake level	To the West	High bacteria counts, but generally good chemical quality.

Site, County, Legal Location	Geomorphic Setting	Bedrock Stratigraphy	Bedrock Permeability Characteristics (Likely fluid and gas migration zones are underlined)	Surficial Materials Stratigraphy	Surficial Materials Permeability Characteristics (Likely fluid and gas migration zones are underlined)	Aquifer Data			
						Aquifer Name/ Characteristics	Depth to Water	Gradients	General Water Quality
JZ Disposal Warren County NW 1/4, Sec. 10 T. 47 N. R. 1 W. Wright City Quad	Dissected Till Plain	Mississippian Burlington Keokuk Limestone	Generally low permeability where protected by clayey till. <u>Fractures may locally be solutionally enlarged.</u>	Glacial drift locally overlies thick channel <u>sands of preglacial origin.</u>	Till generally displays low permeability. <u>Preglacial channel and outwash may display moderate to high permeability.</u>	Preglacial Channel (Good yields)	50-100 feet (est)	To the North (est)	Good to Poor
						Burlington Keokuk (Poor yields)	100 feet (est)	?	Poor
Mexico Landfill Audrain County NE 1/4, Sec. 24 T. 51 N. R. 9 W. Mexico East Quad	Dissected Till Plain	Pennsylvanian shale, limestone, sandstone and coal.	Generally low permeability. Bedrock is an aquitard.	Silty clay loess over Ferrelview Formation over clayey glacial drift.	Loess generally displays low to moderate permeability. <u>Ferrelview and drift may have relatively high permeability in joints</u>, but typically display low permeability.	Glacial Drift (Generally very poor yields except where glaciofluvial deposits predominate)	20 feet (est)	?	Fair
						Pennsylvanian (Poor yields)	?	?	Fair
——— *Centralia Landfill* Boone County S ½, Sec. 11 T. 51 N. R. 11 W. Centralia NE Quad	Dissected Till Plain	Pennsylvanian shale, limestone, sandstone and coal over Mississippian Limestone (Burlington Keokuk)	Generally low permeability, Pennsylvanian bedrock is on aquitard.	Silty clay loess over Ferrelview Formation over Clayey glacial drift.	Loess generally displays low to moderate permeability. <u>Ferrelview and drift may have relatively high permeability in joints</u>, but typically display low permeability.	Glacial Drift (Generally very poor yields)	20 feet (est)	Northeast	Fair
						Burlington Keokuk (Poor yields)	?	?	Poor, High TDS

N.A. = not available

PEMISCOT COUNTY LANDFILL

PEMISCOT County Landfill is located on the alluvium of the Mississippi River on the river side of the flood protection levee. Groundwater levels fluctuate in response to the river stage but are generally shallow, less than 20 feet below ground surface (bgs). Because of high water levels and the random backfill in the area, test bores on the landfill side of the levee were not developed into gas probes. The two gas probes were placed on the other side of and at the foot of the levee, at the southwest corner of the landfill. The following description applies to the bores finished as gas probes.

Permeability was not consistent throughout this stratified profile. Sand lenses were encountered at various depths which could act as gas migration zones depending upon water retention within the soil profile. Vertical movement throughout the profile could be inhibited by clay and silt layers in the profile. Water was encountered at approximately 5-8 feet bgs perched over a 2-foot silty clay horizon. This zone appeared saturated but contained soil structural characteristics which may indicate increased permeability. When saturated, this zone also could act as a confining layer to retard soil gas movement upward or laterally. When dry, soil gases could move through its soil structure to the surface. The predominance of silt in this soil could also inhibit rapid movement of gases and liquids when saturated. The wells were screened from 6 to 15 feet bgs in an attempt to monitor gas below the wet perched zone and to intercept the predominant gas migration pathway.

At the time of installation a small amount of water was observed in the monitoring well borehole developed by the push-probe method; the following day (approximately 12 hours later) 3-feet of water had accumulated in the monitoring well. Since the filter pack penetrated the silty clay zone, perched water could easily follow this avenue created by the screening interval. This problem was not encountered with the auger bore, suggesting that the action of the auger may have sealed or smeared the borehole in the clay limiting water inflow.

SOUTHEAST LANDFILL

The landfill is located on the alluvium of the Blue River. Groundwater levels may fluctuate in response to river stage but are generally less than 20 feet bgs. All drilling was in the northwest corner of the landfill, opposite to the river, in the vicinity of a freeway overpass.

Southeast LF Set 1

Set 1 was adjacent to an existing groundwater monitoring well (S-3) which had high concentrations of methane in gases sampled from it. Permeability was not consistent throughout this stratified profile. The profile with its Fe/Mn staining from 0-37 feet showed evidence of long term water retention. Roots provide vertical pathways from 0-9.8 feet bgs. The first water-saturated zone was evident at the end of the root zone at ~10 feet; the soil was noticeably dryer under this zone at ~11-14 feet. Water channels, silt coats and sand-silt pockets were encountered from 0-21 feet bgs. Most sand and silt pockets were found from ~5-11 feet; most water channels were found from ~10-14 feet at which point they were plugged by silt and clay. Massive soil structure was observed at 0-2 feet (mechanical compaction). Massive soil structure was also found at ~30-32 feet where it combined with the absence of tubular soil pores from 30-37 feet. These phenomena could help to retard vertical migration of soil gases as may have been evidenced by the presence of a septic odor at the 21-30 feet zone resting on the massive soil structure layer beneath it. The predominance of silt and water in this soil could also inhibit rapid vertical movement of gases and liquids especially in regions where tubular soil pores are minimal and when normal moisture conditions exist. One well was screened over the range 36 to 45 feet, as was the pre-existing groundwater monitoring well S-3. The new well filled rapidly with water and was abandoned. Two other wells were screened above the perched groundwater.

Southeast LF Set 2

Set 2 was between a road and railroad tracks, approximately 200 feet from Set 1. Permeability was not consistent throughout this stratified profile. Compacted surface soils are underlain by a layer of asphalt at ~2 feet.

Porous soil structures and evidence of historic water presence increased with depth. Most soil porosity appeared to be from tubular soil pores and water channels at the 10 foot depth. The asphalt seal serves as a confining layer which results in substantial horizontal gas movement. Wells were set at a depth of 10 feet to determine if any shallow migration of landfill gases was occurring above the perched water zone.

ED MEHL LANDFILL

Bores were drilled near the highway on the south side of the landfill. The soils at this location are formed in cherty sediments and material weathered from dolomite, chert and sandstone. This soil, the Doniphan series, consists of very thick, well drained, highly permeable soils with low available water capacity. The regional water table is 100 feet or more bgs but perched water may occur at various depths owing to permeability contrasts in the multilayered residual soils.

Permeability was not consistent throughout this stratified profile. Although chert fragments were present in all horizons, the percentage of chert was variable. Rock fragments, clay skins, roots and soil pores providing pathways were encountered at various depths. These structures could serve as water or gas migration zones depending upon water retention within the soil profile. The presence of mottled soils from 4-9 feet confirmed the permeability of the soil to water. Vertical movement throughout the profile could be retarded by water atop relic chert layers or beds. The predominance of silt and clay in this soil could also inhibit rapid vertical movement of gases and liquids when saturated. Fractured chert and sandstone layers could transmit landfill gases rapidly when not saturated by water. They would rapidly transmit gases horizontally when the overlying horizons were saturated with water or were frozen. Rapid movement of soil gases could also take place under drought conditions.

Well set depths were limited by refusal at 10 feet in one area and 7 feet in the other, in part to determine if shallow wells, less than 10 feet deep, could be used to monitor gas migration. The well sets were placed in a zone of mottled soils with structure pathways formed by historic water movement at 3 to 6 feet and 7 to 10 feet.

MODERN SANITATION LANDFILL

The area tested is near the highway at the northeast corner of the landfill. Thick residuum soils over deeply weathered dolomite, sandstone and chert bedrock predominate at this location. The regional water table is 100 feet below the surface in fractured and solutioned dolomite. Perched water occurs at various depths due to extreme variations in permeability between chert, sandstone and fine-grained soils.

Modern Sanitation LF Set 1

Soil consisted of subangular, blocky fine loam having greater than 20% mottles, with greater than 30% rock to 3 feet bgs. From 3 to 5 feet, layers of clay and clay skins appear in the loam. From 6 to 8 feet, the loam changes structure from subangular and blocky to platy. Pores are very fine to medium with a zone of perched water saturation appearing at 6 feet bgs. From 8 to 10 feet, the loam appears to be granular with greater than 30% rock. The granular loam may serve as a gas conduit for soil gases moving away from the landfill. The water perched zone over the top of this granular layer inhibits vertical gas migration and promotes lateral migration.

The wells were limited to a 10 foot depth by refusal. Gas Monitoring in the open well bore showed high concentrations of landfill gases present.

Modern Sanitation LF Set 2

Set 2 is approximately 100 feet further from the landfill than Set 1. The soils consists of loam or clay with a blocky, subangular structure down to 7 feet bgs. An interval of coarse pores in the soil appears from 4 to 8 feet bgs with fine clay skins appearing above, in and below this clay layer. From 7 to 28 feet bgs, rock content varies from 10 to over 30%; pores are fine to very fine; there are greater than 20% mottles; and the structure remains blocky and subangular down to 28 feet where it changes to granular and then platy.

The wells were set at a depth of 7 to 28 feet bgs to intercept any gas migration pathway found in this zone. Refusal occurred at 28 feet. Gas monitoring in the borehole indicated a strong presence of landfill gases starting at 7 feet bgs.

JZ LANDFILL

Glacial sediments predominate at this location with thick clayey glacial till locally overlying a preglacial channel at depth which is largely composed of fine-grained sand. Gases can easily move through the preglacial channel but may be semiconfined beneath the till.

JZ Sanitary LF Set 1

Set 1 is on a ridge to the north/northeast side of the landfill, near a quarry. Permeability was relatively consistent throughout this profile as was the presence of chert and other rock fragments. Rock fragments, clay and silt skins, soil pores and various layers of root remnants were encountered at various depths. These structures could allow gas migration depending upon water retention within the soil profile. Vertical gas movement throughout the profile could be inhibited by the large amounts of clay and silt in the soil mass. The predominance of silt and clay in this soil would also inhibit rapid vertical movement of gases and liquids when saturated. A gravel zone at 13 feet could allow rapid gas movement laterally.

Refusal occurred at 15 feet bgs; the interval from 6 to 15 feet was screened. Gas monitoring of the well bore indicated a strong presence of landfill gases at approximately 10 feet bgs.

JZ Sanitary LF Set 2

Set 2 is on the opposite side of the landfill, approximately centered on the south perimeter, near a gravel road, and also closer to another landfill which could impact the wells. Permeability was relatively consistent throughout this profile, but many similarities exist with the soils from monitoring set #1. Chert and other rock fragments were consistent throughout the profile. Rock fragments, clay and silt skins, roots, soil pores, and various layers of root remnants which provide pathways were encountered at various depths. These structures could allow gas migration depending upon water retention within the soil mass. Vertical gas movement throughout the profile could be inhibited by the large amount of clay and silt in the profile. The zone from 2-8 feet bgs was very wet. The predominance of silt and clay in this soil would also inhibit rapid vertical movement of gases and liquids when saturated with water. The dolomite gravel zone at ~13 feet could allow very rapid gas movement laterally and could connect with the landfill to rapidly transmit landfill gases. Samples from the gravel zone at 15 feet had a strong landfill gas odor even after weeks in a refrigerated container.

Refusal occurred at 15 feet bgs and the interval of 6 to 15 feet was screened to take advantage of the gravel zone. Gas monitoring of the well bore indicated the strong presence of landfill gases about 8 feet bgs.

MEXICO LANDFILL

Wells were set on the west side of the landfill, adjacent to a farm field. Windblown loess over more clayey glacial deposits are present at this location. Loess thickness is about 5 feet. Glacial material is composed of accretion gley deposits of the Ferrelview Formation (6-8 feet thick) over a thick glacial till sequence. The Ferrelview may act as a confining bed to downward migration of water and upward migration of gas.

Permeability was not consistent throughout this stratified profile although all horizons showed some degree of permeability. The upper 5 feet showed signs of manmade mixing. The soils from 5-10 feet were highly plastic with a high degree of shrink/swell potential. From 10-16 feet the soils were very dense due to increased clay content. The horizon between 12-15 feet showed prizmatic, oblique angled fracturing at the following locations: 13.5, 13.8, 14.0, 14.5, 14.9, and 15.1 feet.

Wells were screened from 7 to 19 feet to intercept gas migration pathways and to approximate the depth of the landfill. Gas monitoring of the well bore indicated high concentrations of methane.

CENTRALIA LANDFILL

Wells were placed near the south perimeter of the landfill, at the edge of a golf course. Gas monitoring of one well bore indicated high concentrations of landfill gases in the soil before well placement. The geology of the Centralia Landfill is characterized by windblown loess over clay-rich glacial deposits. The upper 8 feet of material is composed of modified loess. Below 8 feet, the Ferrelview Formation was encountered to the termination of boring at 12 feet near the top of a thick glacial till sequence, and at the approximate depth of the landfill.

Permeability was not consistent throughout this stratified profile although all horizons showed some degree of permeability. The upper 4 feet showed signs of manmade mixing. The horizons from 7-12 feet were very dense due to increased clay content. The horizon between 8-12 feet showed prizmatic, oblique angled fracturing at the following intervals: 8.5, 8.9, 10.5, 10.4 and 11.2 feet. Roots and soil pores were found throughout the profile. These structures could allow gas migration depending upon water retention and shrink/swell cycling within the soil profile. Vertical movement throughout the profile could be inhibited by clay and silt layers in the profile. The predominance of silt and clay in this soil would also inhibit rapid vertical movement of gases and liquids when saturated. The large prizmatic fractures at 8-12 feet could allow rapid gas movement laterally especially during dry conditions.

The well screen was set at the 6 to 12 feet interval, where methane was detected in the well bore.

Well Types

Three wells were installed 3 feet apart at each site into a known landfill gas migration pathway. To compare wells, it was necessary to ensure that a set of wells was installed where each well would monitor the same zone of methane gas migration. Typically, the push-probe rig drilled first. Gas probe details were set by information obtained from this rig which were then matched with the auger rig. All wells were completed at the surface with 12-18 inches of concrete.

The three types of wells are listed below:

> **Micro-Well**: These wells were installed by using a Geoprobe™ unit which uses push probe technology. With this system, a 2-inch hole could be driven to a maximum of 60 foot depth. Prepacked screens manufactured by GeoProbe™ (½ inch inside diameter x 3 foot length) were used with ½ inch risers for well installation at all sites. Sand was placed over and 6 inches above the screen. The Geoprobe™ (model # 420U) was mounted on a two-wheel drive pickup. Because of the need to carefully seal the small annular gap between the 2-inch hole and the ½ inch riser, a bentonite slurry was placed by tremie. The pressure during injection may have compromised some sand filters.

> **Code Well**: This type of well was installed according to current Missouri Monitoring Well Code regulations. A 6-inch hole was bored with 3-1/4 inch hollow stem augers, using the department's Simco 4000 auger rig which is mounted on a 1-1/2 ton flat bed truck. Wells were completed with 2-inch screens and risers with a sand pack over and 6-inches above the screened length to collect migrating gases. Sand was placed in some wells by successively removing the auger and pouring sand around the well screen in the bottom of the well. A majority of the wells were constructed in open bore holes. The wells were sealed using bentonite slurry. In deeper holes, the bentonite was placed by tremie on top of the sand pack, to force excess air out of the hole and to assure an effective seal.

Modified Well: This is a modified version of the Code Well, with the modifications being use of pea gravel pack instead of sand, and the use of a ½ inch riser instead of the normal 2-inch riser. The ½ inch riser was sealed above the screen with a specially made reducer. The objective was to reduce purge time for deeper wells.

The Code and Modified wells were installed by MDNR-DGLS personnel experienced in using the DGLS rig and installing wells. Similarly, the Micro wells were installed by MDNR-ESP personnel experienced in using the ESP rig and installing wells. Care was taken to not compromise well quality by placing rigid time or budget constraints on the crews. Each crew basically set its schedule, and repair, maintenance and supply expenditures, to reflect the best reasonable practice.

Sets of wells at each site were installed as similarly as possible with regard to depth, screen intervals, riser intervals and seals. However, a variety of seal thicknesses were used from site to site to test the effectiveness of bentonite slurry in eliminating air intrusion from collected samples. Wells installed for this portion of the study are presented in Table 2.

Well Caps and Seals

Sealing the top of the well became a major chore during this task. First, it was found that the angle at which the risers were trimmed played an important part in sealing the wellhead. The risers trimmed square to the length of the pipe sealed better than those pipes cut at an angle. Second, a variety of caps and sealing methods were tested under laboratory conditions simulating seasonal variations of heat and cold. It was found that the PVC risers contract and expand differently than the PVC caps. Therefore, under different temperature conditions, ambient air could intrude into the sample as indicated by the presence of oxygen. It became apparent that fittings on the wells had to be airtight because regulations do not allow the use of glue in joints, couplings and caps. At first, silicon sealant was used to replace conventional PVC glue. It was found that silicon sealant was affected by cold temperatures and allowed air intrusion. Caps sealed with silicon sealant were also difficult to remove to test for water levels, which was done when is was suspected that water was blocking the screened intervals of some wells.

Several types of caps were then tried and it was found that two types of quick connecting caps performed best. For the ½ inch risers, Colder Products has a plastic fitting designated PMCD10-02-12, which has an 1/8" inch, pipe thread mount female fitting attached to a ½ inch PVC friction fitting cap. The second piece of this fitting, a hose barb designated PMC 22-04-12, was attached to the gas meter with ¼ inch polyethylene tubing. The second type of quick connect cap is an EX-Cap Manufactured by Enviro Design Products, Inc. This cap fits the 2-inch risers. It was found that these caps with quick connectors increased the ease and accuracy of sampling soil gases by minimizing air intrusion. Colder Product caps were used for all Micro wells and Modified wells. EX-Cap caps were used for all Code wells. The EX-Cap was particularly effective in minimizing air intrusion of the cap during sampling.

Wells sealed with bentonite slurry with a concrete seal through the frost zone were found to provide the best seal from air intrusion. Earlier trials indicated that bentonite chips do not fully seal and hydrate even when placed and hydrated in 1-foot lifts. This lack of complete hydration allowed more air intrusion into the well. This problem is more severe in the small diameter wells as the bentonite chips would not completely fill the annulus in a well. The effectiveness of the bentonite slurry was shown in a test at a landfill when a Micro well was placed and subsequently dug out to inspect the well seal. The bentonite slurry seal completely filled the annulus from above the well screen to the surface, a depth of 10 feet in this test.

Table 2 - Well Installation Summary

	Material Within Screened Interval	Micro Well	Code Well	Modified Well	Total Depth (ft)	Location of Screened Interval (ft, bgs)	Location of Filter Pack Interval (ft, bgs)	Seal Interval ** (ft, bgs)
Pemiscot County	Clay for Levee	PE 02 L 15 S	PE 01 G 15 S		15	6-15	4-15	0-4
Southeast Landfill 1	Alluvium		SE 01 G 45 S	(SE 06 X 52 S) * **	45	36-45	33-45	0-33
			SE 02 G 10 S		10	7-10	6.5-10	0-6.5
			SE 03 G 6 S		6	3-6	2.9-6	0-2.9
Southeast Landfill 2	Alluvium		SE 05 G 10 S	SE 04 G 10 G	10	4-10	2.5-10	0-2.5
Mehl- 1	Residuum (Chert/Clay)	EM 03 L 6 S	EM 04 G 6 S		6	3-6	2-6	0-2
Mehl- 2	Residuum (Chert/Clay)	EM 01 L 10 S	EM 02 G 10 S		10.6	4.6-10.6	2.6-10.6	0-2.6
Mehl	Residuum (Chert/Clay)		EM 05 G 18 S *		18	13-18	11-18	0-11
Modern	Residuum (Chert/Clay)	MS 01 L 10 S	MS 02 G 10 S	MS 03 G 10 G	10	2-10 (4.5-10.5 for 01)	2-10 (2-10.5 for 01)	0-2
Modern	Residuum (Chert/Clay)	MS 04 L 28 S	MS 05 G 28 S		28	7-28	5-28	0-5
JZ-Set 1	Glacial Till (Clay)	JZ 01 L 15 S	JZ 02 G 15 S	JZ 03 G 15 G	15	6-15 (9-15 for 01)	4-15	0-4
JZ-Set 2	Glacial Till (Clay)	JZ 04 L 15 S	JZ 05 G 15 S	JZ 06 G 15 G	15	6-15	4-15	0-4
Mexico	Loess/Ferrelview (Silt/Clay)	MX 01 L 19 S	MX 02 G 19 S	MX 03 G 19 G	19	7-19	5-19	0-5
Centralia	Loess/Ferrelview (Silt/Clay)	CA 01 L 12 S	CA 02 G 12 S	CA 03 G 12 G	12	6-12	4-12	0-4

*Pea gravel used in place of sand.

**Including approximately 1.5 ft concrete

*** This is a groundwater monitoring well (S-3), previously established for other reasons, which was not constructed according to any of the three specifications used here.

Well Installation

Well sets were installed using various lengths of bentonite seals. In some cases it was desired or necessary to sample gases from the 3 to 10 foot depths because of water or refusal, or because gas was known to be in shallow depths. This ultimately led to the failure of several wells because the bentonite slurry froze within the frost zone of the soil. Field tests completed on bentonite slurry indicated that frost expansion openings appeared which allowed air intrusion through the seal. The wells first affected by bentonite seal failure were at the Ed Mehl Sanitary Landfill. It was found that gas monitoring wells installed to a depth of 10 feet or less may be difficult to seal depending on screen length, height of filter pack above the top of screen and seasonal climate variations. Subsequently, wells installed after the initial failure were installed with a minimum of two feet of bentonite slurry beneath the frost zone and a concrete seal through the frost zone for riser integrity and stability. It is noted that the micro wells were more susceptible to seal failure than the code wells at shallow depths at Ed Mehl. It is not known whether this is inherent in sealing the small annuler space with the micro wells or if it was a result of different construction, such as different seal lengths actually achieved (e.g. 6 inches vs 10 inches).

Sample Collection, Handling, and Analysis

The wells were tested by selected members of the study team on a weekly basis using a LandTec GA-90 infrared gas analyzer, which measures the concentrations of oxygen, carbon dioxide and combustible gases, mainly methane. This machine has a 500 cc per minute electric pump to draw gas samples into the detector. The operator began by connecting the air purged machine to the well and starting the pump. Readings were stored at approximately 1 to 20 second intervals until the reading stabilized. This machine records percent methane, percent oxygen, percent carbon dioxide and percent remaining gases as well as the time and date of the sample. Readings were stored in the machine's memory and downloaded directly into a computer to minimize human error. The data were analyzed with the Excel version 7.0 in a Microsoft Windows NT support package. Tables 3, 4, 5, and 6 show the results of monitoring the wells for successive weeks in March 1997.

Data Interpretation

Throughout the initial phases of well monitoring it became apparent that air was leaking into the wells from around caps or seals at the tops of the wells. This tended to lower the methane readings in wells and elevate the oxygen readings. This problem was more pronounced in the Micro Well designs. Two things were done to minimize this error. First, well caps and seals were improved as discussed above. Second, a method was developed to interpret the data to determine the amount of oxygen due to air intrusion into the well and to calculate a methane reading corrected for air intrusion into the well.

All of the data were plotted on separate graphs of sampling time vs. gas concentrations. All measured gases (CH_4, CO_2, O_2, balance gases) were placed on these graphs. These were then analyzed visually and mathematically for the five criteria below:

1) percent oxygen in the well;
2) percent oxygen explained by air intrusion;
3) percent methane corrected for the amount of air intrusion;
4) time for the methane readings to stabilize; and
5) quality of the curve.

These five criteria are explained in detail below:

I. Percent Oxygen

Percent oxygen measured was taken as the average of oxygen readings after the well appeared to stabilize. Oxygen in the sample was assumed to indicate the intrusion of atmospheric air in the sample.

Application

1) If the percent oxygen is close to zero, the sample does not include substantial amounts of intruded air.
2) If the percent oxygen is near the amount that appears in a standard atmosphere (21 percent by volume), the sample does include substantial amounts of intruded air.
3) Oxygen levels between these extremes represent varying amounts of air intrusion.

II. Percent Oxygen Explained by Air Intrusion

The importance of oxygen as a measure of the amount of air intrusion was estimated by comparing the amount of oxygen that was present with the balance of gases in the sample. It is assumed that the balance of gases is nitrogen. By comparing this nitrogen content to the standard ratio of the concentrations of oxygen to nitrogen in the atmosphere, an internal check on the data could be obtained as the % O_2 explained by air intrusion. This provides an indication of the importance of air intrusion, as opposed to O_2 or N_2 present in the soil gas.

$$\%\,O_2 \text{ explained by air intrusion} = \frac{\%\,O_2 \text{ measured} \times 100}{\%\,O_2 \text{ that would have been measured if the } N_2 \text{ had come from air intrusion}}$$

$$= \frac{\%\,O_2 \text{ measured} \times 100}{\frac{21\%}{78\%} \times \%\text{ Balance of gases}}$$

$$= \frac{\%\,O_2 \text{ measured} \times 100}{\frac{21\%}{78\%} \times (100 - (\%\,CH_4 + \%\,CO_2 + \%\,O_2))}$$

Application

1) If this = 100%, All O_2 measured can be attributed exactly to air intrusion
2) If > 100%, there is more O_2 than can be attributed to air intrusion so O_2 must be present in soil gas
3) If < 100%, there is less O_2 than can be attributed to soil gas so N_2 must be present in soil gas.

III. Corrected Methane Concentration

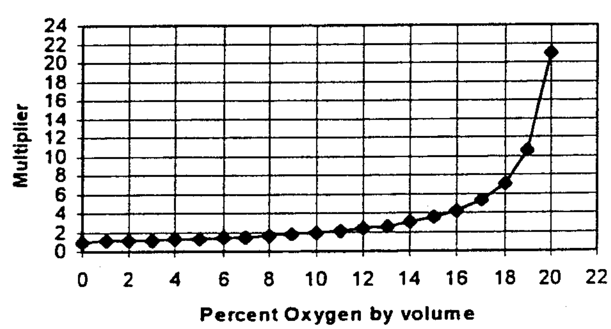
The % CH_4 measured was corrected for the amount of air in a sample by estimating the percentage of a sample that was air from the oxygen concentration. For this criterion, it is assumed that all oxygen in a sample is from air intrusion. This assumption can be checked by criterion II above. The correction was developed as follows:

$$\text{Fraction of air in the sample} = \frac{\%\,O_2}{21\%}$$

$$\text{Fraction of soil gas in the sample} = 1 - \frac{\%\,O_2}{21\%}$$

$$\%\,CH_4\text{, corrected} = \frac{\%\,CH_4\text{, m}}{1 - \frac{\%\,O_2}{21\%}}$$

Figure 3. Sample Correction Factor



If a well has an excellent seal, the % O_2 in a sample from it should be zero at least for most depths sampled here. In this case there is no methane correction. At the other extreme, if a well is poorly sealed, much air will be drawn into the sample, diluting the soil gas being analyzed. The correction factor will increase greatly as more air is pulled into a sample.

Figure 2 provides the multiplier for the measured methane concentration correcting it for air intrusion.

IV. Time for Stabilization

The time for the gas readings to stabilize during each sampling event was taken from an inspection of the sample time curve. This lag time was the time needed to stabilize the measured gas concentrations for methane, carbon dioxide and oxygen. The calculated value for percent oxygen explained by air intrusion did not always stabilize but if it did the remaining values for measured gases and for corrected methane were also stable. The corrected methane concentration typically appeared to stabilize before the measured gas concentrations stabilized. The times were typically less than five minutes but sometimes were as high as 27 minutes in large diameter wells. Concentrations recorded for each sampling are typical values after the lag time.

V. Curve Quality

Quality of the curve is a visual evaluation of the corrected methane curve, aided by the other four criteria, after the lag time. It will be used as the basis for well comparisons and success rate evaluations to follow. Curve quality was set up on a scale of 1 to 3. A value of 1 was given to curves that had consistent values for the measured gases, the measured concentrations of oxygen in the well were reasonable (usually less than 10 percent by volume) and there was good confidence in the corrected methane value as representing the true soil gas composition. A value of 3 on the other hand, was given to a set of readings that had fluctuating values for the measured gases, the measured concentrations of oxygen in the well were inconsistent or high (usually greater than 15 percent by volume) and there was little or no confidence in the corrected methane value. A value of two indicates readings that were moderately acceptable.

Examples of good, intermediate and poor response curves are presented in Figures 3 , 4 and 5, along with summary values for each reading.

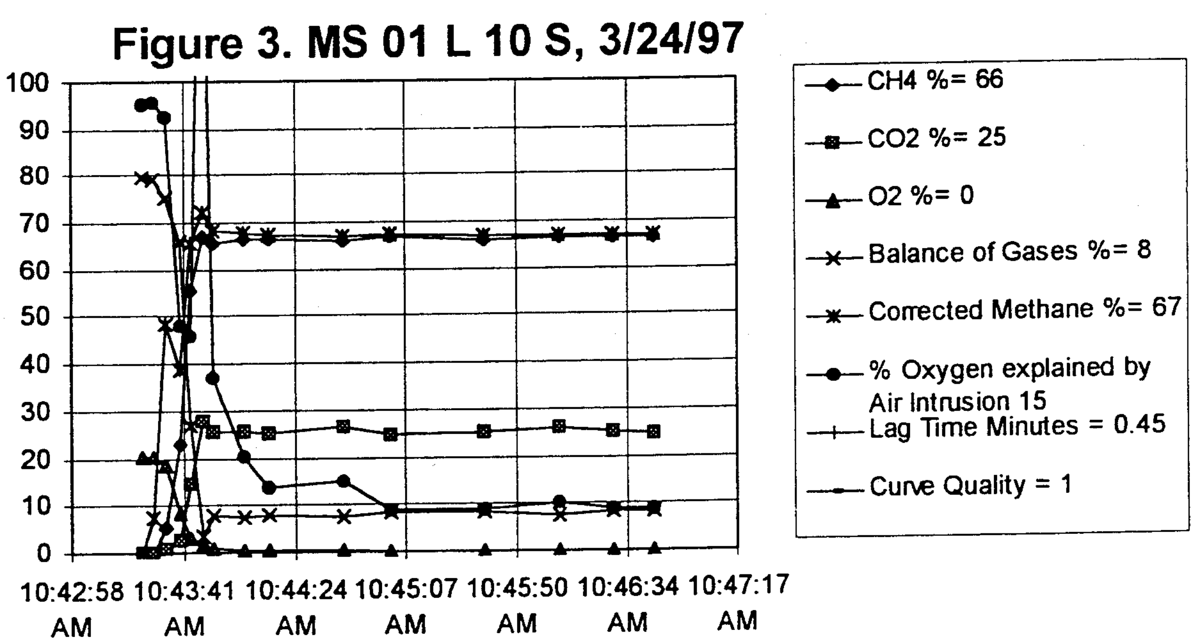


Figure 4. MS 02 G 10 S, 3/24/97

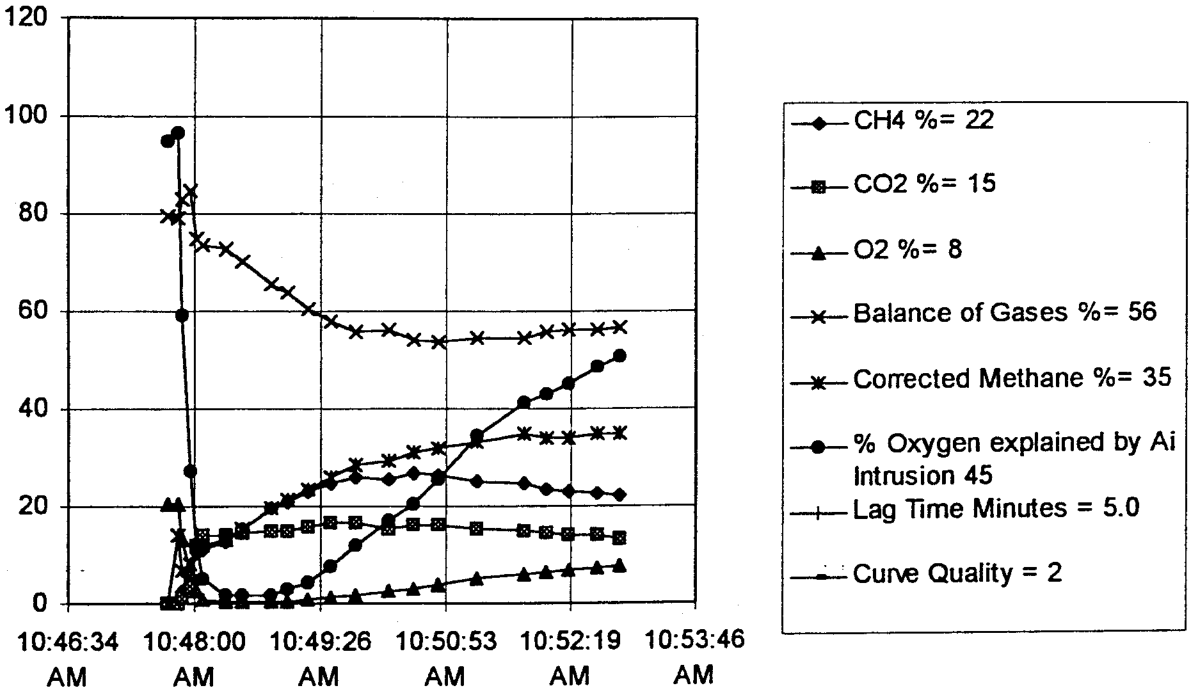
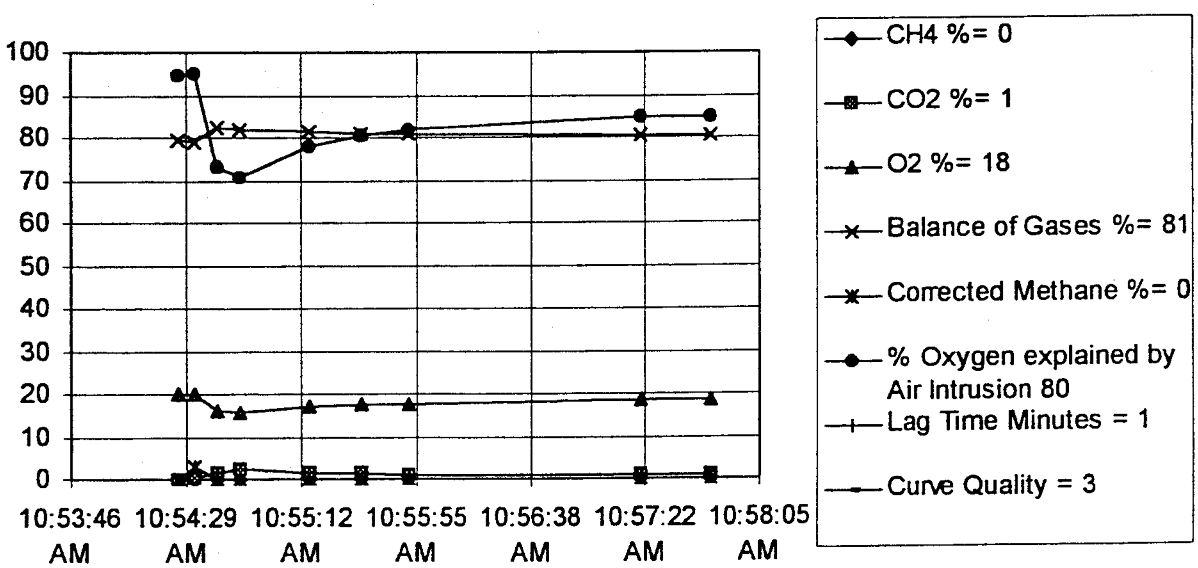


Figure 5. MS 03 G 10 G, 3/24/97



It was found that once the curves for methane, carbon dioxide and oxygen stabilized, the data collector could be confident of the best readings for a given well at a given time. After the plots were prepared, the value of corrected methane appeared to stabilize as fast or faster than the gases being measured. Figure 3 above , is a typical illustration of a curve that stabilized quickly and remained stable, giving a curve quality value of 1. Figure 4 shows an initial instability, then a general trend of stability, for a quality value of 2. Figure 5 shows a sample diluted greatly by air intrusion for a quality value of 3. Later sampling events showed improved readings. This improvement in results was attributed to sampling by more experienced personnel and to better seals and caps.

RESULTS AND DISCUSSION

Location and Installation

The wells at four landfills were considered atypical and monitoring results were dropped or required special consideration. In all cases, however, observations are noted and incorporated herein.

PEMISCOT COUNTY LANDFILL

The wells at the Pemiscot County Landfill were the first to be installed. Soon after installation, water began filling the Micro well and gas readings indicated no methane. The Code well gave 15% CH_4 over a period of many minutes. These wells were not used for subsequent monitoring mostly because of the remote location.

SOUTHEAST LANDFILL

The wells installed at the Southeast landfill were monitored by landfill personnel. The data were suspect based on variability and reasonableness and are not included here. Additionally, it is noted that two wells installed around groundwater monitoring point S-3 did not seal through the perched water zone and were plagued with water covering the screened interval (SE01G45S and SE02G10S).

ED MEHL LANDFILL

The Ed Mehl Sanitary landfill was the second site selected for study. Problems occurred during and after well installation which affected well performance and quality of the results. On the first attempt at well installation, both the GeoProbe and rotary unit met refusal at 6 feet. These wells (EM03L6S and EM04G6S) were finished with cement to a depth of 18 inches leaving only 6" of bentonite seal. This resulted in considerable air infiltration which seemed to affect the micro well more than the code well. Finally, shortly after the wells were installed, an air rotary drilling rig was used to install code and modified wells for another project task at the site. Unfortunately, because of the proximity of drilling to existing wells, the air pressure from the drilling process caused damage to the seals. It was decided to substitute Modern Sanitation landfill for Ed Mehl landfill for the well comparison study since it had a similar geology. This report provides date summaries with and without the results from the Ed Mehl Sanitary Landfill.

MEXICO LANDFILL

A problem was detected while installing a Micro well at the Mexico site. Standard installation calls for macro coring a 2-inch hole, which involves pushing a 2 inch tube into the soil which is then filled by the core. The result is relatively little lateral soil displacement. After the initial hole has been established, a 2½ inch point on a 2¼ inch riser is driven into a 2-inch hole to set the screen and riser. In the clayey soil at Mexico, it was observed that the larger point smeared the soil in the area of the screened portion of the well. A pretest of gas concentrations before the 2¼ inch pipe was employed indicated 40-50% methane by volume in the bore hole. After the well was installed methane concentrations dropped to almost zero. This indicated that the use of the 2½ point and the 2¼ inch pipe to set the screens and riser with Micro wells would smear the borehole sides in tight clays. Because of poor quality data from the Micro well at Mexico, data sets for well performance are shown with and without Mexico results. Micro wells installed in tight soils without using the 2¼ inch pipe after this initial failure were successfully completed at the Centralia Sanitary Landfill, and later at Mexico (after this project closed). The augered wells were successful even in these tight, moist soils.

In the Journal of Geotechnical and Geoenvironmental Engineering, of July, 1997, a paper by X. S. Li, J. Holland, G. Wang and C. J. Roblee on Analysis of Stress-Change Disturbance Caused buy Ideal Drilling in Clay, discusses disturbance for sampling soil caused by changes in stress conditions, by changes in water content and void ratio, by disturbance of the soil structure, by chemical changes, and by mixing and segregation of soil constituents. Readers wishing for further information are referred to authors such as these for a more critical review of interactions within the soil.

It is noted that several factors complicate direct comparisons of well installations and locations. There is always the possibility that different soil gases or geology exists within a well set. Even though wells were located near each other and finished at the same depths, etc., differences may exist other than well types. Assignment of quality values to each reading is somewhat subjective, but did attempt to take inherent site variability into account.

Comparison of Well Types

The data reductions as taken from the plots of gas concentrations appear in Tables 3 through 6, along with comparative well performance using curve quality numbers.

Well comparisons are summarized in Figures 7-9, which indicate the number of readings of well sets for which a particular well performed better than or equal to another well.

Figure 7. Code vs. Micro

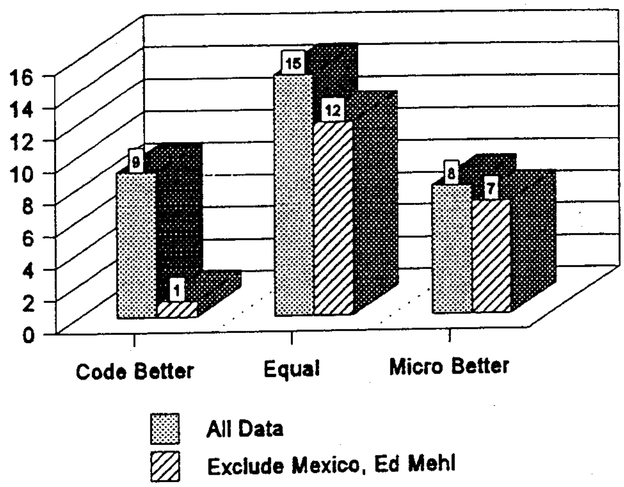


Figure 8. Code vs. Modified

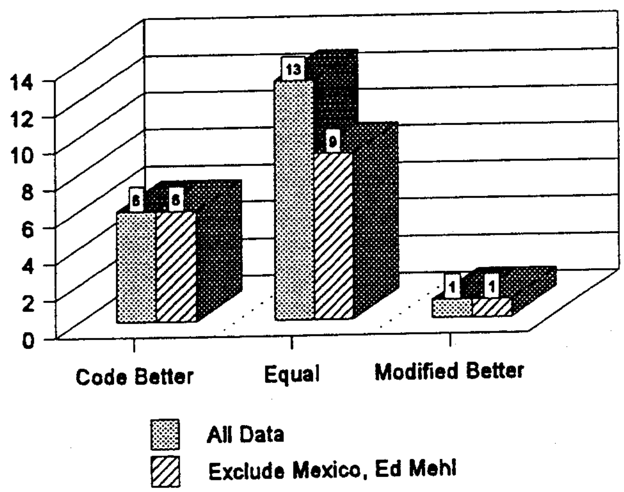
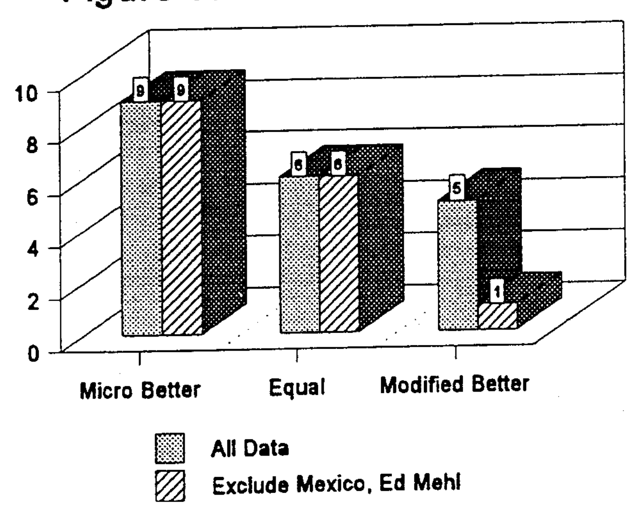


Figure 9. Micro vs. Modified



In Figure 7, the Micro wells overall appear to perform as well as the Code wells, with most readings indicating equal performance, and a similar number of readings indicating the Code or Micro well was better. If Mexico and Ed Mehl results are removed, the Micro wells performed better than the Code wells. In Figure 8 the Code wells are shown to have performed better than the Modified wells. In Figure 9 the Micro wells were superior to the Modified wells, especially if the Mexico and Ed Mehl results are excluded.

Performance of Individual Wells

The problem with well comparisons is the need for two or three wells, forming a set, to be available and tested so a direct comparison can be made. Using the curve quality number, a value judgement is available indicating the quality of the result each time a well was tested irrespective of the presence or testing of other wells.

Table 7 indicates the percentage of readings for each well type that are considered good and reliable (quality rating 1), and those considered unacceptable (quality rating 3). The Code wells gave the highest percentage of good readings, but perhaps more importantly, had the lowest percentage of unacceptable readings. If Mexico and Ed Mehl readings are excluded, the Micro wells performed better and had the highest percentage of good readings and no unacceptable readings.

Table 7. Percentage of Readings for Quality 1 and Quality 3

	Micro Wells	Code Wells	Modified Wells
Good Reliable Reading	69%	72%	55%
(w/out Mexico, Ed Mehl)	90%	60%	44%
Unacceptable Reading	25%	8%	35%
(w/out Mexico, Ed Mehl)	0%	15%	44%

Departmental Installation Cost Comparisons

At total of 29 wells were installed at 7 landfills to complete this task. Total installation costs, including equipment, supplies and labor are presented in Table 8. These figures include costs associated with routine maintenance and repairs.

Table 8. Departmental Installation Cost per Well					% Expenditure Comparisons	
Well Type	Wells Installed	Personal Services	Equipment/ Supplies	Total well costs	Personal Services	Equip/ Supplies
Micro Well	9	$2,103.00	$248.09	$2,351.09	89%	11%
Code Well	14	$3,314.55	$577.45	$3,892.00	85%	15%
Mod Well	6	$3,314.55	$667.45	$3,982.00	83%	17%

From Table 8, it cost 65% more to install the average Code well than a Micro well and 69% more to install a Modified well than a Micro well. It cost 3% more to install a Modified well than a Code well. Down time due to equipment failure is not included in Table 8. It is noted, that the auger rig is 30 years old ,leading undoubtedly to some inefficiency and lost time; however, since equipment failure is not included in Table 8, most of these costs are excluded here. The push-probe rig was new, which perhaps reduced down time but also contributed to de-bugging time, etc. During the two months it took to install all 29 wells, the auger rig broke down a total of four times while the GeoProbe™ rig did not break down. The GeoProbe™ rig was easier to maneuver over bad terrain and in wet weather than the auger rig. On five occasions, the auger rig became stuck, requiring a tow truck on three occasions. Again, these additional costs are not considered in Table 8. It is noted the push-probe rig was faster to set up and take down, and advanced the bore hole faster than the auger rig. These factors are reflected in Table 8.

General Discussion and Conclusions

This report compiled data from 22 gas monitoring wells installed at five landfills to determine the ability of different well construction techniques to produce wells with accurate soil gas samples. Additional wells were installed at two other landfills, but results could not be included here. Knowledge gained from these wells is, however, incorporated throughout this report.

The major issue addressed in this study was to determine if 2 inch Micro wells, installed by the push-probe technique are acceptable for soil gas sampling. The 6 inch code well is the standard in Missouri and is used as a basis for comparison. This comparison considers two sub-issues: (1) the effect of bore diameter (6 inch verses 2 inch) and screen and riser diameter (2 inch verses ½ inch), and (2) the use of the push probe verses the auger to construct the bore.

(1) Borehole, Screen and Riser Diameter
Regarding borehole diameter, it is obvious that the larger the borehole, the greater the flow of soil gas into the well; however, this is offset by the need for more soil gas to fill the well and be sampled. Further a larger borehole diameter provides increased opportunity to sample gas from a larger volume of soil, reducing the chance of non-representative gas samples. This would be particularly important in non-homogenous soils such as clay with cracks or cavities,or multiple layers or lenses of different soils as encountered at most of the sites tested here. There is no evidence in this study that one size of borehole was superior in providing representative soil gas samples, in spite of the non-homogeneous soil conditions encountered at most of the sites tested.

It was expected that a ½ inch screen and riser would result in faster purge times, reducing the time required for sampling, than a 2 inch screen and riser. In fact, the goal of the Modified well design with a 2 inch screen connected to a ½ inch sampling tube (inside a 2 inch riser) was to decrease sampling time, especially for deep wells. The use of a 6 inch hole with the 2 inch screen and a 2 inch hole with the ½ inch screen complicates any effect of screen and riser diameter alone. The results of this study show no consistent differences in sampling time required to reach stabile gas analyses with any of the three well designs. Individual wells may differ within a set, and a given well may vary in sampling time from one week to the next, but the average times for stabilization were essentially equal at 6.2, 6.5 and 6.2 minutes for the micro, code and modified wells, respectively, from Tables 3-6. The average for the micro wells excludes one very long stabilization time of 27 minutes which was much longer than any other sampling at any other well, or even for that well at the other three samplings (each of which was 1 minute).

One aspect of concern in setting borehole and riser diameter is the ability to seal the annular space. The micro well, with a narrow space between the 2 inch hole and the ½ inch riser did appear to be more prone to sealing difficulties, especially in wells installed early in the study and in shallow wells where the length of the slurry seal was minimal. Slurry seals as little as 6 inches were used in this study and were found to be prone to air leakage. Slurry seals at least 2 feet long are recommended, especially with the Micro wells.

(2) Push Probe Verses Auger

Smearing of bore hole walls was evident during this study, especially in fine, moist soils. The push-probe rig, using the 2 ½ inch point to widen the hole prior to screen and riser placement, did smear the well at Mexico. By not widening the hole cut by the soil coring tube, well performance was satisfactory. The auger has the possibility to smear the well in fine soils, but this did not happen here as augured wells in fine soils were successful.

The cost of installing Micro wells was less than the cost of installing code or modified well on a per well basis. This is due primarily to the relatively short set-up and take-down time and the more rapid hole advance time of the push probe rig compared to the auger rig.

There has been some concern regarding the ability of the push-probe rig to operate in a rocky-cherty soil. In general, when one rig was unable to operate upon refusal, the other rig experienced similar problems at the same depth. It appeared that the ability of the larger auger rig to work through some rock and stoney layers by breaking up fragments and stones, etc. was off-set by the ability of the push-probe rig to work through cracks or gaps in layers because of the smaller size of the probe.

The major problem encountered in the study was air intrusion into a well, lowering methane concentrations. Methods used to reduce this problem were better caps, slurry seal placed by tremie and of appropriate length below the frost depth, and generally, care in well construction and sampling. Also, a method was developed to mathematically adjust soil gas composition values for air intrusion and to flag marginal well performance when air leakage is a problem. This method proved to be workable and helpful in analysis and interpretation of the data.

As expected, well design and installation were less critical in coarse soils and in areas with high methane concentrations. As soils become finer and/or wetter, and as soil methane concentrations become lower (such as further away from a landfill), well construction and sampling methods became more critical. This study showed, however, that even in difficult situations, both Code and Micro wells with the improvements noted in this report performed satisfactorily. It is likely the modified design would have performed better if time and other constraints had allowed refinements similar to the improvements made for both Micro and Code wells.

Wells constructed early in the project without the improvements, particularly the Micro wells, performed poorly. The Micro wells at Pemiscot, Ed Mehl and Mexico (the first attempt in fine, clayey soils) all failed or gave marginal performance. Micro Wells installed in similar soils, but with the various improvements, performed very well with no unacceptable readings (Table 7).

Subject to the sites and conditions of this study, the following overall conclusions are offered:

1. Considering all the results of this study, there was no difference in performance between the Micro and Code wells.
2. If data from wells installed early in the study without the improvements noted in this report are excluded (specifically Ed Mehl and Mexico landfills), it is clear from Table 7 that the Micro wells performed better than the Code Wells.
3. Modified wells did not perform as well as either the Micro or Code wells.
4. Sealing of wells from air intrusion is critical in obtaining good soil gas analyses.

Table 3. Results of Gas Well Monitoring from 3/3/97 to 3/7/97

Gas Well	Quality*	Time (min)	%CH4	%O2	%CH4COR	%O2 via int.	Micro vs Code**	Modified vs. Code**	Micro vs. Modified
EM01L10S	3	2	1	20	3	95	C > Mi		
EM02G10S	2	6	5	13	15	70			
EM03L06S	1	1	18	1	19	5	Mi > C		
EM04G06S	2	1	27	10	52	74			
EM05G18S	1	1	21	9	36	60			
MS01L10S	1	1	67	0	68	15	Mi > C	C = Mo	Mi > Mo
MS02G10S	3	1	3	13	10	70			
MS03G10G	3	1	1	17	2	75			
MS04L28S	1	1	72	0	73	20	Mi = C		
MS05G28S	1	1	63	0	65	22			
JZ01L15S	1	2	54	3	63	47	Mi = C	C > Mo	Mi > Mo
JZ02G15S	1	1	48	4	62	56			
JZO3G15G	2	4	15	15	51	88			
JZO4L15S	1	1	42	2	48	26	Mi = C	C = Mo	Mi = Mo
JZO5G15S	1	1	28	5	40	42			
JZO6G15G	1	1	32	6	44	40			
MX01L19S	3	2	3	10	5	50	C > Mi	C = Mo	Mo > Mi
MX02G19S	1	3	33	8	48	68			
MX03G19G	1	2	42	5	55	60			
CA01L12S	2	1	13	15	57	93	Mi = C	C > Mo	Mi > Mo
CA02G12S	2	2	18	15	58	110			
CAO3G12G	3	5	10	20	100	110			

*1 - Good, consistent readings 2 - Marginal data but problems encountered 3 - Inconsistent, variable, never reaches stability

Table 4. Results of Gas Well Monitoring from 3/10/97 to 3/14/97

Gas Well	Quality	Time	CH4	O2	CH4COR	%O2 via int.	Micro vs Code	Modified vs. Code	Micro vs. Modified
EM01L10S	3	1	2	18	10	75	C > Mi		
EM02G10S	1	1	11	8	16	42			
EM03L06S	1	1	20	1	21	4	C = Mi		
EM04G06S	1	1	33	7	50	58			
EM05G18S	1	1	27	7	38	50			
MS01L10S	1	1	71	0	72	23	Mi > C	C > Mo	Mi > Mo
MS02G10S	2	4	8	12	18	63			
MS03G10G	3	1	1	13	2	60			
MS04L28S	1	1	70	0	71	8	Mi = C		
MS05G28S	1	1	63	1	66	22			
JZ01L15S	1	2	54	3	65	43	Mi = C	C = Mo	Mi = Mo
JZ02G15S	1	2	57	2	61	19			
JZO3G15G	1	2	65	0	65	1			
JZO4L15S	2	27	42	4	52	34	C > Mi	C = Mo	Mo > Mi
JZO5G15S	1	2	30	5	40	35			
JZO6G15G	1	2	33	7	50	51			
MX01L19S	3	2	2	12	5	61	C > Mi	C = Mo	Mo > Mi
MX02G19S	1	1	43	5	59	52			
MX03G19G	1	2	61	1	63	16			
CA01L12S	1	5	40	7	61	63	Mi > C	C = Mo	Mi > Mo
CA02G12S	3	7	19	10	36	59			
CAO3G12G	3	1	3	19	23	93			

Table 5. Results of Gas Well Monitoring from 3/17/97 to 3/21/97

Gas Well	Quality	Time	CH4	O2	CH4COR	%O2 via int.	Micro vs Code	Modified vs. Code	Micro vs. Modified
EM01L10S	3	2	1	19	18	92	C > Mi		
EM02G10S	1	1	14	4	17	22			
EM03L06S	1	1	20	3	24	20	C = Mi		
EM04G06S	1	1	41	5	54	48			
EM05G18S	1	1	24	8	39	56			
MS01L10S	1	2	71	1	73	0	Mi > C	Mo > C	Mi > Mo
MS02G10S	3	1	5	7	7	34			
MS03G10G	2	1	20	3	24	22			
MS04L28S	1	1	72	1	75	25	Mi = C		
MS05G28S	1	1	65	2	70	63			
JZ01L15S	1	1	58	2	63	28	Mi = C	C = Mo	Mi = Mo
JZ02G15S	1	1	56	1	59	16			
JZO3G15G	1	1	64	0	64	0			
JZO4L15S	1	1	48	1	49	7	Mi = C	C = Mo	Mi = Mo
JZO5G15S	1	1	30	5	38	29			
JZO6G15G	1	1	42	1	45	10			
MX01L19S	3	1	1	12	3	60	C > Mi	C = Mo	Mo > Mi
MX02G19S	1	1	43	5	55	48			
MX03G19G	1	1	58	0	59	7			
CA01L12S	1	5	45	4	57	43	Mi > C	C > Mo	Mi > Mo
CA02G12S	2	1	20	10	40	68			
CAO3G12G	3	1	11	15	38	83			

Table 6. Results of Gas Well Monitoring from 3/24/97 to 3/28/97

Gas Well	Quality	Time	CH4	O2	CH4COR	%O2 via int.	Micro vs Code	Modified vs. Code	Micro vs. Modified
EM01L10S	3	1	6	16	17	90	C > Mi		
EM02G10S	1	1	15	1	16	6			
EM03L06S	1	1	19	3	22	16	C = Mi		
EM04G06S	1	1	44	3	52	35			
EM05G18S	1	1	22	8	36	55			
MS01L10S	1	1	66	0	67	15	Mi > C	C > Mo	Mi > Mo
MS02G10S	2	5	22	8	35	45			
MS03G10G	3	1	0	18	0	80			
MS04L28S	1	1	68	1	70	15	Mi = C		
MS05G28S	1	1	66	1	68	33			
JZ01L15S	1	1	54	3	65	74	Mi = C	C = Mo	Mi = Mo
JZ02G15S	1	1	60	1	61	16			
JZO3G15G	1	1	64	1	65	28			
JZO4L15S	1	1	48	1	51	18	Mi = C	C = Mo	Mi = Mo
JZO5G15S	1	1	31	3	37	26			
JZO6G15G	1	1	37	3	41	21			
MX01L19S	3	1	1	10	3	58	C > Mi	C = Mo	Mo > Mi
MX02G19S	1	1	43	5	55	72			
MX03G19G	1	1	56	1	58	39			
CA01L12S	1	4	54	2	60	48	Mi > C	C > Mo	Mi > Mo
CA02G12S	2	1	15	12	37	80			
CAO3G12G	3	1	8	16	33	89			