PROPOSED SOLUTIONS TO LANDFILL GAS CONTAMINATION OF GROUNDWATER

Richard Prosser, P.E.
Daniel Waineo, E.I.T.

ABSTRACT

As landfill gas (LFG) migrates from a landfill, non-methane organic compounds (NMOCs) travel with it. These NMOCs have been known to contaminate groundwater. This paper looks at groundwater contamination mechanisms caused by landfills. It also evaluates different methods of slowing or eliminating this contamination. The five basic mechanisms that cause groundwater contamination as a result of landfill activity are: 1) direct contact of groundwater by LFG, 2) LFG cooling in the soil causing condensate water formation and percolation to groundwater, 3) LFG contamination of the vadose zone and infiltrating water or rising groundwater washing contaminants from the soil, 4) leachate leaving the landfill and migrating to the groundwater, 5) acids in the LFG and/or a reducing environment caused by oxygen depletion in the vadose zone causing some naturally occurring metals in the soil to dissolve into the groundwater.

This paper supplements one presented by Richard Prosser in October 1995 at the San Diego American Society of Civil Engineers (ASCE) Conference and is included in the proceedings (1).

INTRODUCTION

Landfill Gas (LFG) testing performed on a number of California landfills demonstrates that most LFG contains some non-methane organic compounds (NMOCs) (2, 3). These contaminants include organic acids, chlorinated hydrocarbons, and numerous other classes of hydrocarbons. The contaminants of greatest concern are typically the chlorinated hydrocarbons, benzene, toluene, ethylbenzene, and xylene (BTEX). This is because some of these hydrocarbons may be a health risk even at low concentrations. The subsequent movement of these constituents to groundwater may result in concentrations exceeding state or federal drinking water standards.

Most of the landfills in the U.S. are affected by the presence of NMOCs in the underlying groundwater. In a study (2) of the results of monitoring RCRA Appendix IX (40 CFR parts 264 and 265) compounds at 479 disposal sites, 84 percent of the detectable compounds were NMOCs. The most commonly occurring compounds were the chlorinated hydrocarbons, including the 8 most frequently detected compounds. Methylene chloride was the most commonly detected compound followed closely by trichloroethene and

---

Richard W. Prosser, P.E., President, GC Environmental, Inc., (714) 632-9969
Daniel Waineo, E.I.T., GC Environmental, Inc., (714) 632-9969

tetrachloroethene. Each of these compounds was detected at over 20% of the landfill sites tested. Because LFG frequently emanates from a landfill into the surrounding soils, there is a possibility that LFG was either the primary source of contamination or a strong contributor. The reason for this assertion is discussed in this paper.

LFG CONTAMINATION MECHANISMS

The four basic mechanisms that cause groundwater contamination by NMOCs in LFG within the vadose zone are described briefly in this section and are shown on **Figure 1**, LFG Contamination Mechanisms.

1. Direct contact with groundwater by LFG

LFG migrating from a site tends to travel the path of least resistance. Generally that path is towards the atmosphere. Two dimensional finite element modeling has shown that LFG can migrate downward prior to escaping to the atmosphere. Because groundwater creates a no flow barrier to convective flow, downward gas movement is primarily by diffusion. As LFG reaches the capillary zone, the NMOCs in the LFG have a good opportunity to be absorbed into the groundwater.

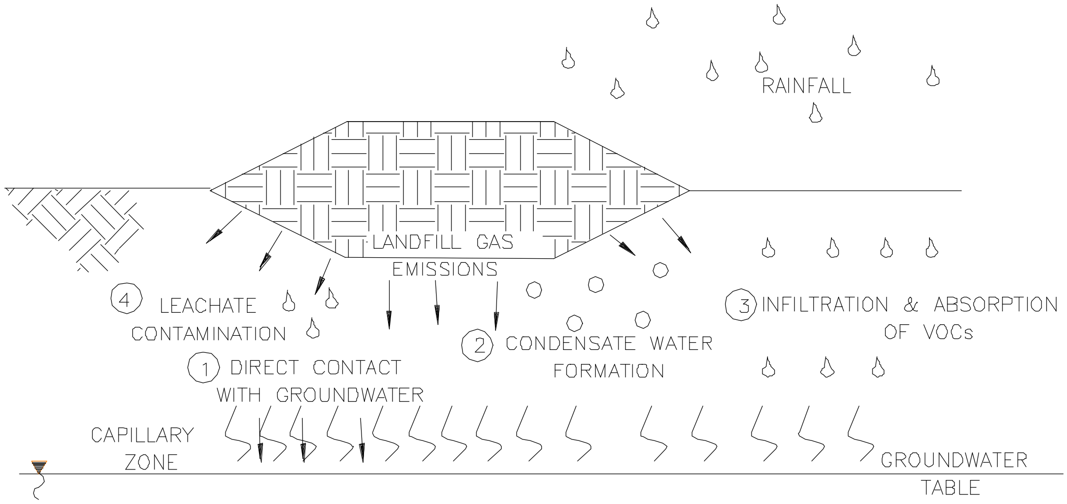


Figure 1: LFG Contamination Mechanisms

2. **Formation of landfill gas condensate in the soil adjacent to the landfill**

   Landfill gas temperatures typically range from 27 to 49° C (80 to 120° F) within a landfill. As LFG moves through refuse, it is saturated with water vapor at these conditions. The soil surrounding a landfill is usually cooler, and for discussion purposes, is assumed to be 16° C (60° F). The difference in these two temperatures will result in the formation of condensate water in the soil. Partitioning of NMOCs from the LFG to the condensate water will result in trace concentrations of NMOCs in the condensate.

3. **LFG contamination of the vadose zone and infiltrating water or rising groundwater washing contaminants from the soil**

   As LFG migrates through the soil adjacent to a landfill, the NMOCs in the soil may be absorbed by water. As rainwater, irrigation or other water infiltrates from above, it reaches equilibrium with the NMOCs present in the soil. Provided these NMOCs are not consumed by bacteria or stripped from the water, they may eventually reach groundwater. Similarly, rising groundwater will wash contaminants from the soil.

4. **Leachate**

   Leachate passing through refuse has full exposure to all contaminants present in the landfill and in the LFG. Leachate draining through the landfill bottom will add to groundwater contamination.

There are other contributing mechanisms that can enhance or interfere with the above contamination mechanisms. For instance, diurnal barometric pressure changes causes barometric pumping to occur. This mechanism can cause gas in the soil to alternately be under positive pressure and vacuum (4) thus increasing convective LFG flow. The soil type can also effect the movement of LFG. Highly fractured rock, sand or other permeable soil types can increase LFG movement. Conversely, low permeable unfractured rock (e.g., sandstone) will limit soil gas movement.

Henry's Law

The four mechanisms described above are all subject to vapor phase contamination dissolving into water. A simple vapor phase calculation to estimate NMOCs in water can be made using Henry’s Law. Henry’s Law is expressed as follows:

$$x_{NMOC} = \frac{p_x}{H_{(T)}} \qquad (1)$$

where;

x_{NMOC} = Aqueous concentration of the NMOC
$H_{(T)}$ = Henry’s Law constant at specified temperature
p_x = Partial pressure of the NMOC

To demonstrate the partitioning of NMOCs between the water phase and the vapor phase, LFG is assumed to contain vinyl chloride as the only contaminant. The assumed vapor phase concentration is 1 ppmv.

Vinyl chloride concentration in water (either leachate or condensate) would therefore be:

$$x_{VC} = \frac{1\text{x}10^{-6}(1\ \text{atm})(62.5\ \text{g/g mol})(1\text{x}10^{6}\ m\text{g/g})}{(1.07\text{x}10^{-2}\ \text{m}^3\text{atm/g mol})(1000\text{L/m}^3)} \qquad (2)$$

$= 5.8\ \mu\text{g/L}$ Vinyl Chloride (Note: MCL for VC = 0.5 μg/L)

There are a number of assumptions that typically are made when applying Henry's law. These include 1) gases behave ideally, 2) other dissolved NMOCs and solids in the water do not hinder the solubility of one another, 3) the water and vapor phase have had intimate contact and are at equilibrium, 4) the temperature is constant (increasing temperature will decrease gas solubility thus releasing gas from solution, and decreasing temperature will cause the liquid to be unsaturated), 5) partial pressure of the solute is less than 1 atmosphere.

LANDFILL GAS MOVEMENT

Landfill gas moves via two mechanisms, convection and diffusion. In landfills, convection occurs because of a pressure build-up in the waste caused by the gases produced from decomposing waste and/or by barometric pressure changes. Diffusion occurs because of a difference in the vapor phase concentration of gases. Diffusion will move gas components from areas of higher concentration to areas of lower concentration.

Based on data that we have collected and reviewed, Gas Control Engineering (GCE) believes that both of these gas movement mechanisms are significant and contribute to groundwater contamination. Convective flow has the potential to move more gas than diffusion. However, once the convective movement of gas is shut off (by the installation of an active LFG extraction system), groundwater contamination appears to continue, although at a reduced rate. It is hypothesized that this continued contamination is primarily caused by diffusion.

IS IT LANDFILL GAS OR IS IT LEACHATE?

This is a question that needs to be answered at every site. In the 1960s and 1970s most practitioners thought that leachate was the primary source of groundwater contamination. If one looks at the contaminants in groundwater adjacent to a landfill, it commonly looks like leachate is the cause. Contaminants typically include increased metals, increased NMOCs and decreased pH. These are all characteristics of leachate, but they are also characteristics of landfill gas contamination, although metals are not transported by LFG. However, some of the naturally occurring metals in the soil can be dissolved into the groundwater by the LFG.

The interesting thing about LFG contamination is that it can occur upgradient and cross gradient from a landfill. The mechanisms by which LFG causes metal and NMOC contamination are discussed below.

Increased Metals: There are two mechanisms by which LFG causes increased metals in groundwater. As LFG comes in contact with groundwater, the carbon dioxide and organic acids dissolve in water to form weak acids. These acids can then dissolve naturally occurring metals into groundwater. For instance, iron oxide (FeO or Fe2O3) is listed as insoluble in water (5). Iron oxide is, however, soluble in acid (5). Many other metals behave similarly.

Additionally, LFG can create a reducing environment in the vadose zone below a landfill. Oxygen that would normally be present in the vadose zone is either consumed by aerobic bacteria or displaced by the LFG. This in turn allows some metals to reduce and become soluble in the groundwater.

Increased NMOCs In Groundwater: Increased NMOCs in groundwater by itself may not be sufficient to determine the relative contribution of the contamination mechanism. However, the potential mass of contamination in gas is typically far greater than the mass of contamination in leachate (1).

Determining the Source, Landfill Gas or Leachate

Determining the primary source of groundwater contamination is not always easy because both LFG and leachate usually cause some contamination. There are four primary techniques GCE uses to help identify the primary source. They are as follows:

1. Be logical: Areas of low precipitation have less opportunity to cause groundwater contamination by leachate because the leachate generation rates are typically low. For these sites, LFG is usually considered the primary mechanism for groundwater contamination. This can be confirmed by other techniques described below.
2. Evaluate the chloride concentration. Leachate typically has a high chloride content. A low increase in chloride in groundwater will usually correspond to a low level of leachate contamination. This is perhaps one of the easiest and best

indicators of leachate contamination. **Table 1** shows a summary of leachate composition at municipal landfills.

3. Look at the carbonate or bicarbonate (carbonate) concentration in the water. Elevated carbonate is usually (but not always) a good indicator of LFG contamination. Our experience has shown that there is not a good correlation of loss of carbon dioxide from the LFG to the increase in carbonate in water. This is most evident when there is an increase in naturally occurring metals in groundwater upgradient or cross gradient from the landfill caused by landfill gas. Under these circumstances, one would expect to see carbonate in high concentrations. This does not always occur.
4. Calculate the mass of NMOCs in groundwater versus the mass of NMOCs in leachate. For this technique, one will need to estimate the leachate and the groundwater flow rate. The concentration of contaminants in the groundwater and LFG will also need to be known. Use Henry's Law to calculate the mass of contamination that can be transferred by the leachate.

An interesting observation was made at one site when comparing the calculated vinyl chloride concentration to the measured concentration. The measured concentration was greater than the calculated concentration based on the measured concentration of vinyl chloride in the gas. There are several explanations for this. First, the solubility of vinyl chloride in leachate is not as great as in groundwater because the leachate is typically warm and the groundwater is cool. Second, carbon dioxide in the LFG may have reacted in the soil, thus decreasing the CO_2 concentration in the LFG. This has the effect of concentrating the remaining gases. This, in turn, can increase the contaminant concentration in groundwater. Third, the measured vinyl chloride concentration may have been less than the actual concentration due to dilution of the LFG by air in some of the extraction wells.

Another reason to believe that LFG is the primary cause of NMOC contamination of groundwater is that leachate typically does not have saturated concentrations of NMOCs present based on calculations or compared to measured NMOC concentrations in LFG condensate water. A possible explanation for this is that once leachate pools on the bottom of a landfill, some of the NMOCs are removed from the leachate by sparging. Landfill gas (methane and carbon dioxide) that is generated below the leachate surface will bubble to the surface and remove NMOCs by sparging (bubbling gas through a liquid to remove volatile compounds). A second possibility is that salts and other solids in the leachate reduces the solubility of the NMOCs.

TABLE 1
SUMMARY OF LEACHATE COMPOSITION AT MUNICIPAL LANDFILLS

Component	Units	Overall Leachate Average	Average Leachate Composition as a Function of Age of Refuse (Years)								
			<1	1-2	<2	2-3	2-4	3-5	4-10	5-10	>10
COD	(mg/l)	15,110	27,781	12,104	18,134	23,347	19,429	15,275	7,900	7,056	6,361
BOD	(mg/l)	10,504	24,939	7,390	14,215	15,335	11,375	7,289	4,253	3,470	6,231
TOC	(mg/l)	3,593	9,237	2,971	5,059	4,951	4,253	1,810	1,598	1,598	1,234
pH	(mg/l)	6.29	5.83	6.12	6.00	5.46	6.11	6.65	6.25	6.25	6.66
TS	(mg/l)	15,698	41,032	--	41,032	15,085	10,099	7,250	6,167	6,167	--
TDS	(mg/l)	11,298	26,497	15,952	21,224	14,940	13,633	12,161	5,856	5,856	1,459
TSS	(mg/l)	497	348	661	505	330	540	669	340	361	310
VSS	(mg/l)	303	256	602	371	210	273	308	406	496	170
TVS	(mg/l)	8,835	25,378	--	25,378	4,152	3,320	2,904	--	--	--
Spec. Cond.	(umohs/cm)	6,760	7,467	8,237	7,775	8,294	7,789	6,780	4,779	4,779	3,417
Alkalinity	(mg/l as CaCO3)	3,664	7,169	2,282	5,214	3,793	3,307	2,431	3,379	3,379	1,482
Hardness	(mg/l as CaCO3)	4,255	7,865	1,927	5,886	2,598	5,581	7,073	3,613	3,613	577
Tot PO_4	(mg/l)	6.97	16.85	6.72	12.51	10.74	8.58	2.82	2.48	2.48	2.42
Ortho PO_4	(mg/l)	22.55	66.23	0.17	42.20	5.97	8.50	12.73	6.18	6.18	1.40
PO_4 (inorg)	(mg/l)	3.49	9.15	2.28	4.57	2.35	2.23	1.29	0.89	1.20	8.90
NH4-N	(mg/l)	300.55	434.7	235.4	319.29	325.3	319.32	302.1	220.89	209.7	87.73
NO3+NO2-N	(mg/l)	3.65	8.73	4.68	6.15	1.46	2.15	3.73	0.77	0.74	0.74
Organic-N	(mg/l)	145.63	448.38	90.89	259.12	167.00	132.95	43.18	32.08	37.90	27.38
TKN	(mg/l)	449.45	883	339	580.76	492	452.33	345	217.81	206	200.06
Ca	(mg/l)	1,004	2,456	622	1,377	1,163	1,343	1,705	598	598	166
Mg	(mg/l)	717	308	224	258	348	1,154	2,766	2,010	2,010	115
Na	(mg/l)	702	1,046	920	972	576	577	580	643	643	331
K	(mg/l)	654	1,720	516	998	599	550	387	300	300	172
SO4	(mg/l)	382	667	281	461	674	632	576	51	51	64
Cl	(mg/l)	980	1,356	1,106	1,224	982	997	1,022	1,024	1,024	354
Fe	(Tot-mg/l)	427	1,360	223	691	452	559	717	219	211	121
Mn	(Tot-mg/l)	17.28	28.89	12.60	18.71	22.69	23.94	31.13	955	0.07	2.29
Zn	(Tot-mg/l)	20.89	104.00	17.68	30.01	29.13	26.05	16.07	3.50	1.60	25.99
Cu	(Tot-mg/l)	0.48	0.27	0.54	0.45	0.20	0.44	0.90	0.24	0.29	0.78
Cd	(Tot-mg/l)	0.051	0.075	0.061	0.066	0.037	0.037	0.034	0.071	0.079	0.029
Pb	(Tot-mg/l)	0.517	1.250	0.630	0.754	0.431	0.429	0.248	0.362	0.396	0.684
Hg	(Tot-mg/l)	0.018	--	0.006	0.006	0.014	0.012	0.006	0.005	0.005	0.037
Se	(Tot-mg/l)	0.641	2.700	--	2.700	0.290	0.290	--	0.100	0.100	0.058
Cr	(Tot-mg/l)	0.944	9.100	0.060	4.580	0.207	0.198	0.153	0.155	0.167	0.568
Ni	(Tot-mg/l)	1.21	13.00	0.04	4.36	0.32	0.49	0.75	0.21	0.10	0.65

TDS - Total Volatile Solids
Note: Based on a CH2M Hill search of technical literature on municipal leachate data.
Source: EPA (October 14, 1988b).

THE SOLUTION

In this section we will review how systems have been designed in the past to help reduce LFG contamination of groundwater. We will also explore methods to improve LFG control to better protect groundwater. Some of the concepts presented here are relatively new, hence there is little or sometimes no data available on how they might respond. No specific recommendations are made for any of the designs.

Benefit of Active LFG Collection

Source control using landfill gas extraction wells in the refuse has a demonstrated history of controlling convective and some diffusive gas flow. This is most easily seen when looking how source control can help landfills comply with the 5% methane limit in the monitoring probes at a landfill's perimeter. These systems are modified to improve deep landfill gas collection by using extraction wells with perforations near the landfill's bottom. This type of LFG extraction system, however, has not been able to demonstrate complete protection of groundwater. We believe that the reason for this is because active interior collection is not completely effective in controlling gas diffusion from a landfill's sides or bottom. This is because there is no inward gradient (flow) at a landfill's bottom to overcome the diffusion velocity because there is no air or gas to allow an inward flow.

Possible Solutions

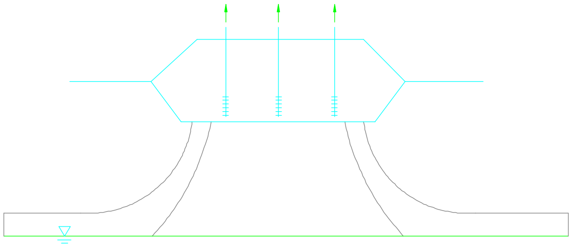
Eight different LFG collection control schematics (**Figure 2**) are presented that may help control subsurface LFG emissions. The shaded zones shown on these schematics is our hypothesis of what the zones of contamination in the vadose zone below the landfill might look like. The darker zones represent possible areas of higher concentration and the light zones are lower concentration. The zones of contamination are only conceptualized because neither finite element modeling nor soil vapor measurements have been made to confirm them.

1. Interior LFG extraction wells
2. Perimeter LFG extraction wells
3. A combination of interior and perimeter LFG extraction wells
4. Interior LFG extraction with perimeter air infiltration wells
5. Interior LFG extraction with perimeter and interior air infiltration wells
6. Interior LFG extraction, interior vadose zone extraction and interior and perimeter air infiltration
7. Perimeter LFG extraction with opposite perimeter air infiltration wells
8. Perimeter LFG extraction with interior air infiltration wells

Each of these systems, by virtue that LFG is being collected, will probably have some positive benefit to groundwater, but, some will likely have more improvement than others. Deciding which system to use is not always easy.

FIGURE 2
LFG COLLECTION CONTROL SCHEMATICS

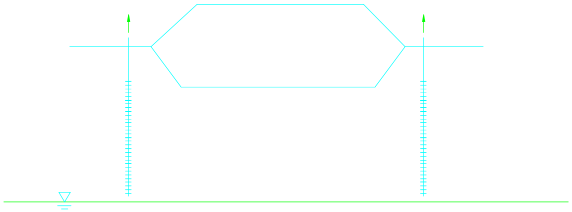
1. INTERIOR LFG EXTRACTION



ADVANTAGES:
1. SOURCE CONTROL
2. POSITIVE INFLUENCE ON LFG EMISSIONS
3. REDUCED CONTAMINATION ZONE IN VADOSE ZONE

DISADVANTAGES:
1. PROBABLY NOT VERY EFFECTIVE AT CONTROLLING DIFFUSION

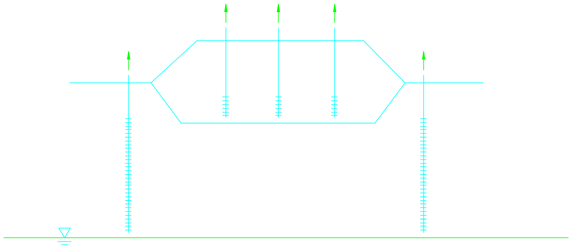
2. PERIMETER LFG EXTRACTION



ADVANTAGES:
1. INCREASED INFLUENCE IN VADOSE ZONE

DISADVANTAGES:
1. PROBABLY NOT VERY EFFECTIVE AT CONTROLLING DIFFUSION
2. REDUCED CONTROL OF LFG EMISSIONS
3. PULLING CONTAMINATION AWAY FROM THE LANDFILL

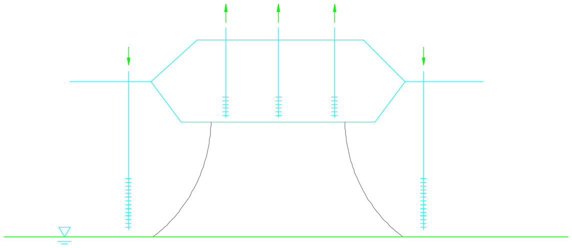
3. INTERIOR AND PERIMETER EXTRACTION



ADVANTAGES:
1. INCREASED INFLUENCE IN VADOSE ZONE
2. POSITIVE INFLUENCE ON LFG EMISSIONS
3. SOURCE CONTROL OF LFG

DISADVANTAGES:
1. PROBABLY NOT VERY EFFECTIVE AT CONTROLLING DIFFUSION

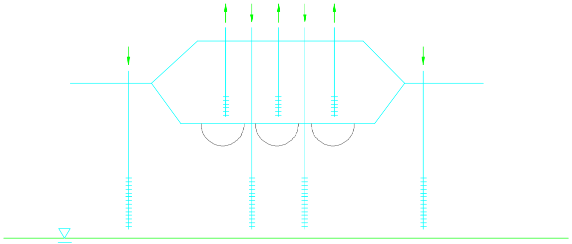
4. INTERIOR LFG EXTRACTION WITH PERIMETER AIR INFILTRATION



ADVANTAGES:
1. SOURCE CONTROL
2. POSITIVE INFLUENCE ON LFG EMISSIONS
3. MORE EFFECTIVE AT CONTROLLING DIFFUSION

DISADVANTAGES:
1. STILL SOME VADOSE ZONE CONTAMINATION
2. INCREASED RISK OF LANDFILL FIRE

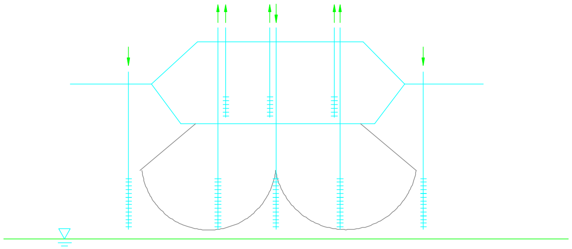
5. INTERIOR LFG EXTRACTION WITH PERIMETER AND INTERIOR INFILTRATION



ADVANTAGES:
1. SOURCE CONTROL
2. POSITIVE INFLUENCE ON LFG EMISSIONS
3. MORE EFFECTIVE AT CONTROLLING DIFFUSION

DISADVANTAGES:
1. INCREASED RISK OF LANDFILL FIRE
2. PENETRATES LANDFILL BOTTOM

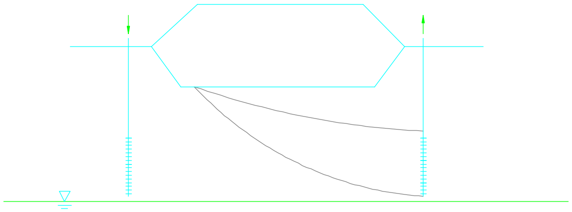
6. INTERIOR LFG EXTRACTION, INTERIOR VADOSE ZONE EXTRACTION, AND INTERIOR AND PERIMETER AIR INFILTRATION



ADVANTAGES:
1. SOURCE CONTROL
2. POSITIVE INFLUENCE ON LFG EMISSIONS
3. MORE EFFECTIVE AT CONTROLLING DIFFUSION

DISADVANTAGES:
1. INCREASED RISK OF LANDFILL FIRE
2. PENETRATES LANDFILL BOTTOM

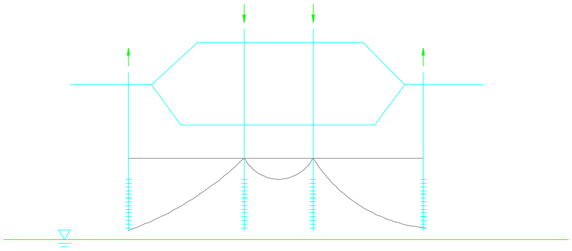
7. PERIMETER EXTRACTION WITH PERIMETER AIR INFILTRATION



ADVANTAGES:
1. INCREASED INFLUENCE IN VADOSE ZONE

DISADVANTAGES:
1. PULLING CONTAMINATION FROM LANDFILL
2. REDUCED CONTROL ON LFG EMISSIONS

8. PERIMETER EXTRACTION WITH INTERIOR AIR INFILTRATION



ADVANTAGES:
1. MORE EFFECTIVE AT CONTROLLING DIFFUSION

DISADVANTAGES:
1. PENETRATES LANDFILL BOTTOM
1. PULLS CONTAMINATION AWAY FROM LANDFILL
3. LESS CONTROL OVER LFG EMISSIONS

PRELIMINARY EVALUATION OF SCENARIOS

The objective of an LFG extraction system is typically to control LFG emissions (convection). Diffusion has traditionally not been the focus of LFG system designs. It should be noted that even if the bottom of a landfill is under vacuum, this does not imply that diffusion is controlled. The reason for this is that there is probably not significant inward gradient at the landfill's bottom because there is not enough sweep air or gas making its way through the vadose zone to overcome the diffusion velocity. Several of the proposed LFG collection control schematics are designed to specifically influence diffusion.

Five mechanisms of groundwater contaminants by LFG were defined at the beginning of this paper. Some of the proposed gas control system alternatives would have a positive influence on all five mechanisms. For instance, if we consider Alternative #5 (Interior LFG extraction with perimeter and interior air infiltration wells) improvements to each of the five mechanisms can be described as follows:

1. Direct contact with groundwater: In this alternative, convective control will limit subsurface LFG emissions. Emissions that do occur will either be diluted with infiltration air or possibly even carried back into the landfill because of the inward gradient at the landfill bottom.
2. LFG cooling and condensate water formation will be reduced because LFG emissions are controlled.
3. LFG contamination of the vadose zone: This system has three benefits. First, future LFG contamination is reduced by active LFG extraction; second, some contamination in the vadose zone will be removed by the sweep air; and third, cometabolism by methanotrophs will further reduce chlorinated hydrocarbons in the soil.
4. Leachate leaving the landfill: When the leachate reaches the sweep air zone, the air will tend to strip NMOCs from the leachate and increase the oxygen content. The O_2 rich leachate will help precipitate solids.
5. Acids in the LFG and oxygen depletion cause naturally occurring metals to dissolve: By adding sweep air, the zone below the landfill is not as likely to become oxygen deficient. Secondly, by controlling LFG in the landfill, carbon dioxide and organic acids will not be able to dissolve naturally occurring metals.

The following is a general rating of the alternatives based on the hypothesized vadose zone contamination below a landfill and ability of diffusion to carry contaminants to groundwater. This rating is very general and is based on the relative zone of contamination remaining in the vadose zone following implementation of the LFG system.

	Diffusion Control	**Convective Control**
1. Interior LFG extraction wells	F	G
2. Perimeter LFG extraction wells	P	P
3. A combination of interior & perimeter LFG extraction wells	F	G
4. Interior LFG extraction with perimeter air infiltration wells	G	G
5. Interior LFG extraction with perimeter and interior air infiltration wells	G	G
6. Interior LFG extraction, interior vadose zone extraction and interior and perimeter air infiltration	G	G
7. Perimeter LFG extraction with opposite perimeter air infiltration wells	G	P
8. Perimeter LFG extraction with interior air infiltration wells	G	P

P = Poor
F = Fair
G = Good

In reality, we don't know how the various types of systems will respond. This leaves room for a considerable amount of future research to be performed. The proposed method of doing this research is to use finite element modeling. Modeling would allow each of the alternatives to be tested for effectiveness and responsiveness substantially faster and at a lower risk and cost than installing actual systems. It would also allow one to determine the effect on LFG system operations without risk to a landfill.

CAUTION TO THE DESIGNER

As with any LFG system, both the design and operation will affect its performance. The landfill gas system must be designed with caution to reduce the opportunity for added contamination to groundwater by draining leachate through an air infiltration well. Also, the risk of landfill fires by allowing oxygen to enter the refuse must be monitored closely. Inward gradient using air below a landfill's bottom creates a higher, but controllable level of fire risk. The design will require adequate separation between the air infiltration wells and the landfill's bottom.

CONCLUSION

Groundwater contamination by landfills is well documented. When the contaminants are NMOCs, the primary source is probably landfill gas. If the contaminants are metals or other inorganics, either leachate or LFG may be the source.

There are two mechanisms that cause LFG movement, convection and diffusion. LFG system design normally focuses on controlling convection. These systems have demonstrated improvements in groundwater quality. For improved success in protecting groundwater from NMOCs, diffusion also needs to be controlled.

REFERENCE SOURCES

1. Prosser R. and Janechek A. "Landfill Gas and Groundwater Contamination". American Society of Civil Engineers Convention, San Diego, CA, October 1995.
2. Plumb Jr., R.H. “The Occurrence of Appendix IX Organic Constituents in Disposal Site Groundwater”. Groundwater Monitoring and Remediation, Spring 1991, pp. 157 - 164.
3. “The Landfill Testing Program: Data Analysis and Evaluation Guidelines”. California Air Pollution Control Officers Association Technical Review Group, Landfill Gas Subcommittee, and California Air Resources Board Summary Source Division, September 13, 1990.
4. Prosser, R. "Effects of Atmospheric Pressure on the Availability of Gas from a Landfill", Proceedings of 8th International Landfill Gas Symposium (San Antonio, Texas: Governmental Refuse and Collection and Disposal Association, 9-11 April 1985)
5. CRC Handbook of Chemistry and Physics, 58th edition, 1977-1978, CRC Press, pp. B82 - B178.