HORIZONTAL GAS WELLS THAT LAST: A CASE STUDY OF PERFORMANCE

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ABSTRACT

For the twenty plus years that horizontal collectors (wells) have been installed to control landfill gas, their use has met with mixed results. The benefits of horizontal wells are well documented. They can be installed without specialized equipment or training in active landfill areas to collect gas immediately after waste placement on a temporary or extended basis. They have been proven to effectively control emissions of landfill gas prior to installation of landfill cap systems. Barriers to their use have been the questionable longevity of the wells and a limited understanding of the basis for design and proper construction of the devices.

This paper documents the case history and performance of numerous horizontal gas wells installed over the past 11 years and presents design and construction techniques proven to increase the efficiency and long-term viability of the wells. The data demonstrates that the performance of these wells has been such that operators may consider forgoing the installation of vertical gas wells entirely or at the least consider reduction and deferral of vertical well installation until final capping and closure.

Historical performance data and installation costs from our database of multiple wells at several landfills were analyzed to evaluate production and longevity in comparison with vertical well installations. The results of that analysis are presented in this paper to provide a cost planning tool for landfill operators considering the use of horizontal gas wells. The documented performance of horizontal collectors over time provides a better understanding and increased appreciation for the role of horizontal gas wells in a well-designed and properly managed landfill gas collection system.

INTRODUCTION

According to the United States Environmental Protection Agency (US EPA) Landfill Methane Outreach Program (LMOP) website (http://www.epa.gov/lmop/basic-info/index.html#a02), municipal solid waste (MSW) landfills are the third largest source of anthropogenic methane emissions in the United States. Landfill gas (LFG) is derived from the anaerobic decomposition of organic matter contained within the MSW at the time of disposal. LFG is typically composed of approximately 50% methane, approximately 50% carbon dioxide, and a very small fraction of the balance gases primarily comprised of nitrogen and non-methane organic compounds (NMOCs).

As documented in the Technical Summary of the Intergovernmental Panel on Climate Change (IPCC) Working Group I Fourth Assessment Report (WGI AR4), methane is considered one of several long-lived greenhouse gases (GHG) which are chemically stable and persist in the atmosphere over time scales of decades to centuries resulting in a long-term influence on climate. The US EPA notes that carbon dioxide, methane, nitrous oxide, and fluorinated gases are considered principal GHGs which contribute to the entrapment of atmospheric heat and are catalysts in climate change (http://www.epa.gov/climatechange/emissions/).

The Code of Federal Regulations, Part 60 – Standards of Performance for New Stationary Sources, Subpart WWW – Standards of Performance for Municipal Solid Waste Landfills requires that owners / operators of MSW landfills having a design capacity greater than or equal to 2.5 million megagrams or if the calculated NMOC is equal to or greater than 50 megagrams per year, install gas collection and control systems (among other conditions and requirements as described in §60.752).

In addition to the federal and, in some cases, supplementary state regulatory requirements for landfill gas collection, the methane within LFG is a well-established fuel source which can be beneficially used in direct use and/or electricity generation applications.

Depending upon the geometry of the landfill, the size of the active disposal area, and the waste acceptance rate, it may take months or even years for active areas to reach their final design grades. LFG generation may occur in these areas before final grades are attained, potentially resulting in odors, as well as safety and/or compliance issues.

While there are numerous types of gas collection devices for extracting LFG from the waste mass, vertical wells can be considered the "industry standard". Despite the need for specialty drilling equipment, the design methodology and construction techniques are generally proven and reliable. However, there are inherent problems associated with constructing vertical wells in active waste disposal areas including:

- safety concerns associated with monitoring and adjustment in high traffic areas;
- proximity to vacuum piping;
- risk of damage from traffic and waste placement operations; and
- the practicality of raising the wells and extracting gas from the waste placed above the originally constructed well segment.

The construction of horizontal gas wells is a feasible solution to collecting LFG in active disposal areas. Horizontal gas wells are not a new concept, but they may be underutilized for a number of reasons including perceived durability / longevity, improper design and/or materials selection, and improper construction techniques.

The installation of a horizontal collector can support odor reduction in active disposal areas which is a public perception and compliance benefit, and should be considered as a strategy to support landfill gas to energy (LFGTE) project viability by potentially providing more gas earlier in the project. Another benefit is the reduction of GHG emissions from early stage LFG generation and organic wastes prone to rapid decomposition.

This paper presents some design considerations which are intended to aid in the successful implementation of horizontal gas collectors. This paper will also present data showing that horizontal wells, when properly designed and constructed, can yield gas for extended periods and work in conjunction with vertical wells.

TECHNICAL CHALLENGES

There are numerous technical challenges to address in designing and constructing a durable horizontal gas well. Primary considerations include effective gas collection, durability, cost, environmental conditions, minimizing impacts to waste disposal operations, settlement, liquid entrapment ("watering out"), ultimate cover depth, construction materials selection, and minimizing air intrusion. Each of these items provides ample material for their own respective study. For the purpose of this paper, the authors will present several design techniques which in their experience consistently address several critical considerations (e.g. settlement, drainage, environmental conditions and pipe selection) for successful horizontal collector installation.

DESIGN CONSIDERATIONS

Settlement

Landfill settlement occurs due to organic waste decomposition, inorganic waste material consolidation, and surcharge loading by continued was disposal over previously placed waste. As noted by Bolton (1995), drainage problems caused by settlement are among the most common landfill problems. Settlement can result in reductions to pipe slopes, pipe buckling, and downhill creep or tilting of vertically oriented structures such as vertical gas wells.

As piping within or on the landfill settles, slope loss results in reduced drainage capacity (discussed in further detail below). Further, due to the variability of the types of materials within MSW and their inherent physical properties, differential settlement occurs. This type of settlement is sometimes apparent on the landfill surface as isolated stormwater ponding, and as gas conveyance piping develops localized low spots which fill with condensate limiting gas flow and occasionally resulting in loss of vacuum to a LFG collection device. It is reasonable to assume this also happens at depth within the waste mass. However, unlike surface piping which can be adjusted to correct the problem, horizontal gas collection piping is inaccessible.

Several design strategies can be used to reduce the adverse impacts of settlement on horizontal gas wells and extend their service life. First, a horizontal gas well should be designed with as much pipe slope as possible. From a constructability perspective, this means starting out with a sloped active disposal area to avoid excavating variable depth trenches to obtain the required pipe slope. A sloped working face generally promotes surface stormwater runoff and establishes the grade for the horizontal collector layout, but it can also present operational inconveniences such as vehicle traction and traffic safety in the winter months. Designers must work closely with landfill operations personnel to plan where and when horizontal gas collectors will be installed.

Over the course of designing and constructing approximately 40 horizontal collectors in the last 15 years, the authors have worked with landfill owners to regularly establish working face slopes of 4-6%. Horizontal gas collector piping should be oriented to coincide with the surface slope direction (perpendicular to contour, or as close to it as practical) to take advantage of the surface slope. If the horizontal gas well is designed as a "loop", inevitably some piping will be constructed at less than the ground surface slope but the design should be configured to optimize the slope. Areas of lesser slope can be addressed by adjusting the excavation depth, and by providing mechanisms for liquids drainage as further described in the next section.

Another useful design strategy to counteract the effects of landfill settlement is the incorporation of multiple vacuum headers. A minimum of two vacuum source connections should be made, and careful consideration should be given to their locations. It is preferable to have one or more connections at the highest elevation points on the horizontal gas well as these areas are less likely to accumulate liquids which may result in a gas flow blockage (e.g. "watering out"). Multiple connection points provide backup vacuum sources for the horizontal gas wells and help protect the capital investment; should an area or vacuum header become watered out, at least one additional vacuum source connected to a different portion of the horizontal well will allow continued collection of LFG from the remaining segment. Vacuum sources can be connected to the lower elevation side of a horizontal gas well but provisions should be made to separate the liquids from the gas flow to avoid inundating the header system.

Flexibility of the piping system is also a consideration in designing for differential settlement. While PVC and HDPE piping systems are generally considered flexible based on their ability to deflect more than 2% without cracking (Moser et al., 1977), the method in which they are assembled must also be considered. By installing the piping in segments (e.g. not butt fusing, mechanically joining, or solvent cementing) and butting the ends after fitting with an oversized pipe sleeve, the piping system retains flexibility for movement during differential settlement. The intent of the sleeves is to provide a semi-flexible joint which allows movement while maintaining the integrity of the pipe opening and preventing stone infill of the perforated collection piping.

Liquids

One of the most significant issues with any LFG collection and control system is the management of liquids within the system. Landfill leachate may seep into LFG collection devices, and condensate is generated as the high humidity LFG cools as it is drawn from the waste mass through the system conveyance piping. Unlike vertical gas wells, which by their orientation, allow gravity drainage of liquids (unless plugged by fines or underlying low-permeability waste), horizontal gas wells must be designed to convey liquids out of the piping to maintain an open flow path for gas conveyance.

Horizontal wells are especially susceptible to liquids inundation as they may be spatially extensive, are typically constructed in active (uncapped) disposal areas and are therefore subject to intercepting infiltrating stormwater, and much like utility corridors constructed in soil, provide a higher permeability conduit and preferential flow pathway through the waste material.

Liquid drainage within a horizontal gas well can be accomplished through several means including pipe slope, vertical drains, and installation of drip/drain legs to convey the liquids to the leachate collection system. The design component of pipe slope was previously discussed with settlement.

Vertical drains, configured much like a vertical gas well, can be incorporated into a horizontal gas well design. Typically, vertical drains would be located at design low points in the piping network to drain liquids migrating through the horizontal pipe trenches. The drains can be drilled or excavated, and are typically backfilled with clean coarse stone such as an AASHTO #3 or AASHTO #57 product.

The authors have used various types of drain or drip legs to aid in gravity dewatering of horizontal gas wells. The drip legs can be designed in many different configurations. One common method involves the incorporation of a drain leg from the design low point (s) of the horizontal gas well. The piping for the drain leg should be installed with as much pitch as possible away from the horizontal to a daylight point on the intermediate or final grade slope. The pipe should be extended to the liner system protective cover material where it can be perforated and partially buried for system drainage. The piping can be connected directly into a leachate collection pipe but a vacuum break (e.g. trap) should be included to prevent the application of vacuum from the horizontal gas well to the leachate collection system. Ideally, this can be done in a location which will remain accessible for trap cleanout / maintenance.

Another variation of the drain leg can be incorporated in combination with a vacuum header connection on the low elevation side of a horizontal gas well. At the point at which a vacuum header daylights on the final or intermediate grade slope, a tee can be installed and oriented vertically. Vacuum is applied from a lateral or a wellhead off the top of the tee, while the in-line connection serves as a drip leg as described above. It is important that the design includes some mechanism to separate gravity liquid drainage from the extracted gas to avoid inundating the gas conveyance system.

Environmental Conditions and Pipe Selection

There are many pipe material options available for consideration in horizontal gas well applications. There are several important factors to consider when evaluating the pipe material for a particular application including:

- the desired life expectancy of the horizontal;
- the vertical spacing / frequency of horizontal gas well installation;
- expected depth of waste and pipe loading;
- the environmental conditions to be encountered including chemical/biological degradation potential and temperature;
- the installation method proposed along with safety considerations (e.g. does pipe joining require manual labor within the trench, depth of trench, etc.); and
- pipe material and installation costs.

High density polyethylene (HDPE) and polyvinyl chloride (PVC) are two of the most common pipe options used in various landfill applications based on their physical properties and ability to withstand biological and chemical degradation typical in MSW landfill environments. Metallic piping, such as galvanized, bitumastic, or polymer coated corrugated metal piping (CMP) has also been used for horizontal gas collectors and various other landfill applications.

Each pipe material has respective strengths and weaknesses in terms of suitability for use in horizontal gas well applications. For example, HDPE has a higher impact resistance than PVC (10-30 times) so it is less likely to incur damage during installation (Zhao et al. 1998). However, HDPE deforms at temperatures greater than 120 degrees Fahrenheit, and landfill gas temperatures of 120 degrees are not uncommon (LandTec, 1994). Various manufacturer and trade industry documents note suggested temperature limits for PVC between 140 and 150 degrees Fahrenheit depending on the application; however, temperature de-rating factors must be applied per the specific manufacturer. PVC pipe modulus of elasticity, or the measure of an objects tendency to deform elastically upon application of force, decreases with increasing temperature. Zhao et al. (1998) also notes that the modulus of elasticity decreases with time for pipes subjected to a continuous load. From a temperature degradation perspective, the modulus of elasticity for CMP is the least affected by typical landfill temperatures in comparison to HDPE and PVC. While less impacted by temperature, CMP is subject to corrosion. While appropriate coatings can be applied to improve its resistance to degradation, these coatings are subject to damage during installation, field perforating, and backfilling.

One of the most critical considerations to pipe selection is also one of the most difficult to evaluate for landfill applications; waste mass lateral passive resistance. In flexible pipe design, designers must recognize that the pipe / surrounding material interaction is the major component of the design (Zhao et al., 1998). Thermoplastic and CMP piping rely on the properties of the surrounding material to counteract the deformation of the pipe resulting from applied loads. MSW contains a variety of materials with a wide range of physical properties. Further, as noted in the settlement discussion section, the density of the waste varies depending upon the specific materials as well as their depth within the waste mass. This variability presents a unique challenge for the designer and inevitably, some assumptions have to be made.

Product specification data from individual manufacturers should be reviewed and evaluated in comparison to the specific site conditions and intended application. The best pipe material for a particular application is largely dependent upon the data obtained through evaluation of the criteria noted at the beginning of this section.

Material and installation costs vary based on a number of parameters including geographic location, raw material pricing, delivery distance, and quantity of the order / installation. The following table presents budgetary material cost for 10-inch perforated pipe for several different types of pipe materials supplied and installed in the northeastern US.

TABLE 1. PIPE MATERIAL COSTS

Typical Piping Materials	**Material Cost/Ft**
10" Dual wall corrugated HDPE	$ 5.40
10" SDR 11 HDPE	$ 15.65
10" SCH 80 PVC	$ 19.00
12" Polymer coated CMP	$ 15.00

Material costs are based on 1,000-ft unit rates acquired from regional suppliers as of January 2012.

Installation costs will vary depending on the connection method selected, but for comparison purposes of this paper, it is assumed that slip-sleeve "joining" of the various pipe options results in a negligible installation cost difference.

CASE STUDY DATA AND RESULTS

For this case study, we analyzed operational data from one (1) site that has multiple horizontal wells designed and constructed using the techniques described above. The wells utilize a 10" perforated HDPE dual-wall pipe that has an outer corrugated wall and smooth inner wall. Each of the horizontal wells selected for the evaluation has drilled vertical condensate drains installed at low points and key locations to promote liquid drainage.

Historical data compiled over the past 11 years was evaluated to help understand the performance and longevity of horizontal gas wells. To assess the effectiveness of the horizontal wells, a series of key comparisons were performed including:

- determination of gas production rates;
- gas production rates over time;
- gas production rates at varying waste depths;
- horizontal well vs. vertical well production rates;
- site flow distribution between horizontal and vertical wells; and,
- horizontal well performance before and after the installation of vertical wells.

The overall data set for the evaluation included gas quality and flow rate readings from one (1) site covering an 11 year period. The site has a total of six (6) active horizontal wells installed; however, two (2) horizontal wells were excluded as they are newer installations with limited operating history. Data for the four (4) remaining horizontal gas wells was validated by removing improbable outlying values and null values. The outliers were values recorded that are outside the range of the monitoring equipment and were considered to be erroneous. Records with null (missing) values for flow rate were also removed from the data set. The final reduced data set included 3,006 readings for the four (4) selected horizontal wells.

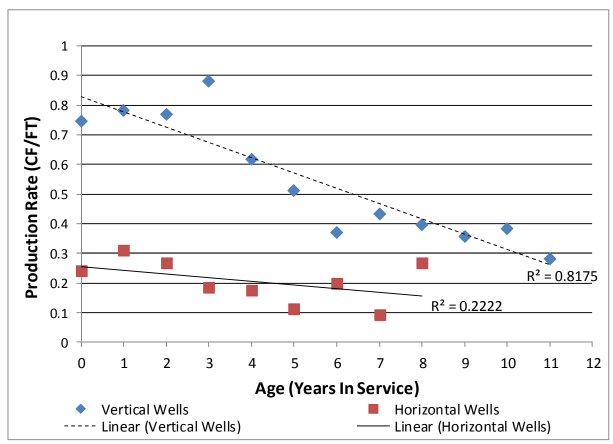
An evaluation of vertical gas well production was required for comparison to the horizontal wells. Similar data reduction and validation methods were used to reduce the vertical well data. The final vertical well data set included 24,470 readings from a total of 83 vertical wells.

The following sections include a discussion of the results of these comparisons.

Gas Production Rates

The gas production rates for the horizontal wells were calculated by taking the linear footage of perforated pipe for each device divided by the flow rate resulting in a cubic foot/foot of pipe (cf/ft) value. Flow rates were also adjusted to a 50% methane basis to normalize the data for comparison. The gas production rates for horizontal wells ranged from 0.31 to 0.094 cf/ft over an 8-year period with an average of 0.21 cf/ft. For comparison, the calculated gas production rate for vertical wells ranged from 0.88 to 0.28 over an 11-year period with an average of 0.54 cf/ft. The calculated production rates for both the horizontal and vertical wells are shown on Figure 1.

FIGURE 1 – HORIZONTAL & VERTICAL WELL PRODUCTION RATES



As shown in Figure 1, the production rate for both horizontal and vertical wells decreases over time. This could be due to numerous factors which may be different for horizontal and vertical wells. A best fit linear regression line is shown in Figure 1 along with the R^2 value for each data set. The R^2 value represents the relationship between two variables with 0.0 being no relationship, and 1.0 representing a perfect relation. In this case, an R^2 value of 0.82 for vertical wells shows a relatively close relation between production rate and the age of a device. Conversely, the lower R^2 value for the horizontal wells shows that there is less of a relationship with the production rate of the horizontal wells over time.

The horizontal wells are installed in the active lift area and precede the installation of vertical wells. For the horizontal wells studied, vertical wells were not installed until the landfill reached final grade. This was on average 2-3 years after the horizontal well was installed for that given area. There is a notable decrease in gas production for the horizontal wells at year 3, around the same time that vertical wells were installed due to distribution of the gas among more collection devices.

The vertical wells are installed at final grade and are generally most productive in the first 1-3 years. Their production begins to decrease around year 4, and continues a downward trend as the waste matures.

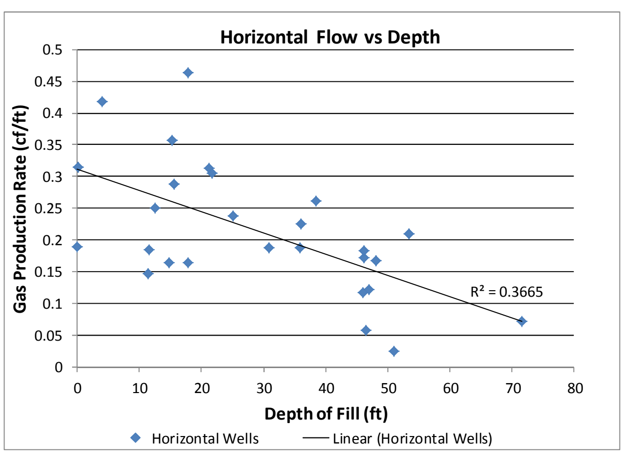
In comparing the production rates of horizontal wells to vertical wells, it is important to note that the vertical wells are more efficient per foot over the life of the device; however, their production rate decreases more rapidly over time when compared to the horizontal wells.

Gas Production at Various Waste Depths

Depth of waste over the horizontal gas wells was evaluated in an effort to identify a critical depth where the devices fail, or provide limited effectiveness. The depth of cover over each horizontal was calculated on an annual basis over the life of the device using tools in AutoCAD®. A surface layer was created using annual fly-over topographic maps for the sites. Point files were then generated along the perforated pipe sections of each horizontal and at intersecting points on the annual topographic surfaces to calculate the depth of waste for each point. The points were then averaged each year to calculate the average annual waste depth for each horizontal well.

Horizontal well gas production rates were plotted against the annual average waste depth as shown in Figure 2.

FIGURE 2 – HORIZONTAL FLOW VS. DEPTH



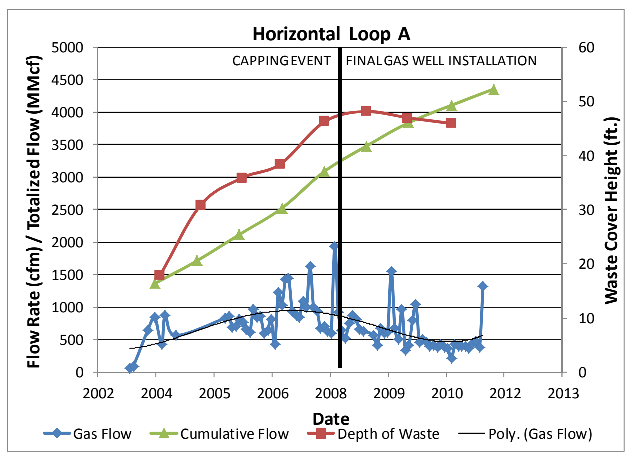
Based on the data, there is a general decrease in gas production over time as waste depths increase. Since the horizontal wells are installed at intermediate fill grades, the depth of waste increases over time until the landfill reaches final design grades. The decrease in production as depth increases may be attributable to several factors including piping system integrity, liquids accumulation, differential pipe settlement, the addition of vertical wells at final grade elevations, and other factors.

A Closer Look

Up to this point, the discussion has focused on general trends for the overall performance of a group of horizontal gas wells. This section takes a closer look at one of the four loops in the data set to show the history of the device and performance in relation to waste depth and influence from vertical wells.

Loop A was the first horizontal well installed at the site. At the time of installation there were a total of 25 vertical wells installed in final capped areas, but no collection in the active area. The horizontal is roughly 4,100 feet long with six (6) drilled vertical condensate drains and three (3) vacuum connections. The loop was installed on an unplanned lift that was not graded specifically for the horizontal well installation; however, pipe slopes of 2-3% were maintained to vertical drains in the loop. Data for the horizontal is shown in Figure 3.

FIGURE 3 – HORIZONTAL LOOP A

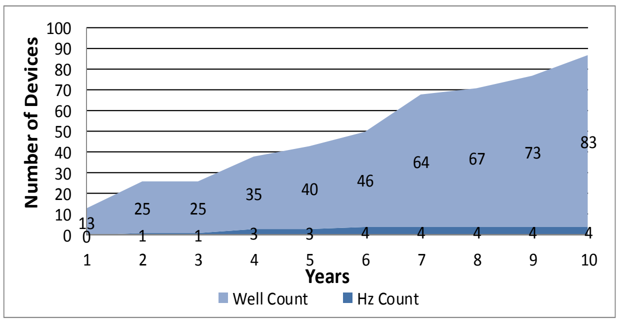


Data plotted for Loop A demonstrates significant long-term gas production and collection over an 8-year period. Gas collection rates generally increased over time up until final grades were reached and the final capping and vertical wells are installed. Gas collection rates generally decreased after the capping event; however, the horizontal remained very productive. The site was able to collect gas from the active area as filling operations progressed without impacting lift operations. The cumulative flow collected prior to vertical well installation is substantial totaling around 3,000 MMcf of LFG.

Horizontal vs. Vertical Well Flow Distribution

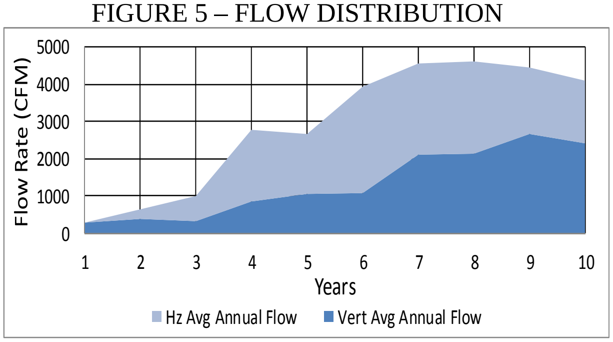
The gas production rate over time is important to understand in determining the effectiveness of horizontal gas collection loops. Gas flow distribution for the site was used to evaluate the collection efficiency between horizontal and vertical gas wells. For this comparison, average gas flow rate data was used for four (4) horizontal gas wells and 83 vertical gas wells. A breakdown of the number of gas wells used in gas flow calculations is shown by year on Figure 4.

FIGURE 4 – COLLECTION DEVICES INSTALLED



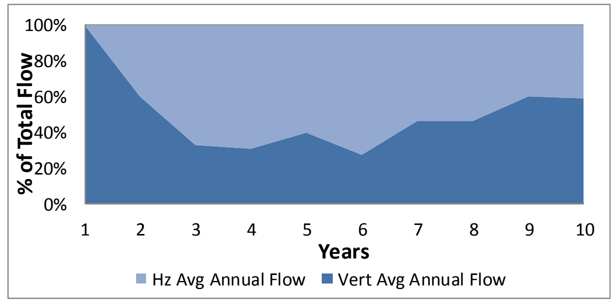
The collected data points shown were gathered over a period of ten (10) years and through multiple phases of gas well construction. Average gas flow rates for both horizontal and vertical gas wells were totalized each year to determine a total average system flow rate for the site. Gas production by year is shown on Figure 5.

FIGURE 5 – FLOW DISTRIBUTION



Horizontal gas wells have the capacity to collect a greater volume of gas than vertical gas wells due to their size resulting in a larger area of influence. On average, gas volumes collected from horizontal gas wells for the study site represents 49.7% of the total gas flow over the ten year period. The percentage of total site LFG flow collected by the horizontal wells peaked at almost 72%. The distribution of gas flow between horizontal and vertical gas wells as part of total site gas flow is shown in Figure 6.

FIGURE 6 – PERCENT FLOW DISTRIBUTION



Although gas collection rates observed from the horizontal gas wells declined following installation of the vertical gas wells, the data shows that these wells are still effectively capturing a significant volume of gas. At year 10, three years after the last horizontal installation, the horizontal gas wells continue to collect nearly 41% of the total site gas flow at the site.

CONCLUSIONS

The horizontal wells evaluated in this study were constructed using dual wall corrugated HDPE pipe based on the economy of the material and ease of construction installation. As noted, all the pipe options presented in Table 1 have respective strengths and weaknesses for horizontal gas well applications. The material properties for dual wall corrugated HDPE present some inherent physical limitations, especially at the typical LFG / waste temperature and potential load conditions encountered. However, based on the evaluation of horizontal well performance data used in this study, there is a valid argument for using the more economical corrugated HDPE material in conjunction with the appropriate design and construction techniques presented.

Further, focusing exclusively on collection device material and installation costs (e.g. no vacuum / gas conveyance piping), actual project construction cost data for horizontal gas well collectors using dual wall corrugated HDPE piping generally falls within the $32-38/ft range, as compared to vertical well construction costs ranging from $73-$93/ft. Considering the investment associated with higher cost vertical well installation in active disposal areas may be at risk due to damage from waste placement or traffic, horizontal gas wells are a cost-effective alternative.

Horizontal well gas flow has been shown to decrease over time due to factors such as increasing burial depth and the installation of vertical gas wells. This decrease in gas collection appears to be gradual as the horizontal wells continue to collect a large percentage of the total gas flow years after installation at varying waste depths.

The perforated HDPE dual walled piping used to construct these horizontals currently operate as designed in waste depths exceeding 70 feet. While no obvious performance depth limitation has been identified in the data, the authors typically recommend horizontal gas well vertical separation of approximately 40 feet within the waste mass when using dual wall corrugated piping based on field experience. This interval should be adjusted based on the pipe material used and the duration of in-place waste to maximize LFG collection as anaerobic decomposition of the organic material begins.

Whether by government mandated regulation, economic benefit, or odor control, landfill gas collection has become a key component of most landfill environmental management systems. The use of horizontal gas wells should be considered for LFG collection and control in active areas. Although vertical gas wells are shown to be more efficient (e.g. yield more gas per foot of perforated pipe installed) in the data set analyzed, horizontal gas wells have been shown to collect large quantities of gas following installation in active areas of the landfill where it is less practical to install vertical gas wells. Proper design methods are critical to their performance and longevity.

Without the installation of collection devices in the active filling areas, LFG generated in the early stages of decomposition may otherwise not be collected increasing the risk for malodors and fugitive GHG emissions. The use of horizontal gas wells is recommended as a consideration for improving overall LFG collection efficiency throughout the landfill life as well as the viability and timing of LFGTE project implementation.

REFERENCES

Bolton, N., 1995, “The Handbook of Landfill Operations," Blue Ridge Solid Waste Consulting, Bozeman, MT.

Code of Federal Regulations, Part 60 – Standards of Performance for New Stationary Sources, Subpart WWW – Standards of Performance for Municipal Solid Waste Landfills (http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c=ecfr&sid=0f9cfd88d16f3f20bafdf66df034de93&rgn=div6&view=text&node=40:6.0.1.1.1.88&idno=40)

Landfill Control Technologies (LandTec), 1994, “Landfill Gas System Engineering Design – A Practical Approach Based on a Decade of Experience” Landfill Gas System Engineering Design Seminar.

Moser, A.P., Watkins, R. K., and Shupe, O.K., 1977, “Design and performance of PVC pipes subjected to external soil pressure.” Buried Structures Laboratory, Utah State University, Logan, UT.

Solomon, S., Qin, D., Manning, M. et al. 2007, “Climate Change 2007 - The Physical Science Basis,” Contribution of Working Group I to the Fourth Assessment Report by the IPCC (ISBN 978 0521 88009-01 Hardback; 978 0521 70596-7 Paperback), Cambridge University Press, New York, NY.

United States Environmental Protection Agency Landfill Methane Outreach Program Basic Information Website: http://www.epa.gov/lmop/basic-info/#a02

United States Environmental Protection Agency Climate Change Website: http://www.epa.gov/climatechange/emissions/

Zhao, J. Q., 1998, “Durability and Performance of Gravity Pipes: A State-of-the-Art Literature Review,” Institute for Research in Construction, National Research Council of Canada, Ottawa, Canada.