Evaluation of the Landfill Odor Problem at the Sunshine Canyon Landfill

Prepared by:
Yazdani Consulting
Ramin Yazdani, Ph.D., P.E.
1800 Birch Lane
Davis, CA 95616
(530) 574-1499

Prepared for:
South Coast Air Quality Management District
21865 Copley Drive
Diamond Bar, CA 91765

August 15, 2015

Table of Contents

Yazdani Consulting
Ramin Yazdani, Ph.D., P.E.
1800 Birch Lane
Davis, CA 95618
Tel (530) 574-1499
Email: ryazdani@sbcglobal.net

August 15, 2015

Mr. Nicholas A. Sanchez
Senior Deputy District Counsel
South Coast Air Quality Management District
21865 Copley Drive
Diamond Bar, CA 91765

Subject: **Evaluation of Landfill Odor Problem at the Sunshine Canyon Landfill**

Dear Mr. Sanchez:

At your request, Yazdani Consulting has reviewed the available data for Sunshine Canyon Landfill (SCL) and has identified potential improvements in the design and operation of the landfill gas (LFG) collection system to reduce gas emissions and odors. The purpose of this preliminary evaluation was to provide a summary of known site conditions, and propose further investigation and potential solutions to better manage LFG collection and control odor nuisance. The results are provided below.

Purpose

Yazdani Consulting was retained by South Coast Air Quality Management District (SCAQMD) to provide consulting services to SCAQMD and to assist Hydro Geo Chem, Inc. (HGC) in the planning, testing and evaluation of the SCL gas collection system using baro-pneumatic testing and computer modeling. In addition, provide ideas for further investigation that would yield better management of the landfill gas collection system and control landfill odor nuisance.

Landfills

When solid waste containing organic materials is disposed in landfills, the waste decomposes anaerobically, resulting in generation of landfill gas consisting mainly of CH_4 (50%) and CO_2 (50%). The gas generation depends on the amount and age of waste in the landfill, the waste composition, nutrients, presence of inhibitory compounds, and the landfill conditions such as temperature, waste moisture, waste pH, waste compaction, and landfill cover design. The landfill gas builds up pressure inside the landfill and the pressure, together with diffusion, causes gas escape from the landfill. As illustrated in Figure 1, the fugitive emission and odor from a landfill occurs through many different escape routes and measuring the individual or total emission rate from these routes is challenging. The generated gas can be recovered by engineered gas collection and removal systems and utilized for energy production, which reduces the overall emissions. The CH_4 emissions through the soil cover and cracks can be mitigated through the use of biocover system where methane is oxidized. However, reliable measurements for quantification of LFG collection efficiency and methane oxidation in biocovers are necessary.

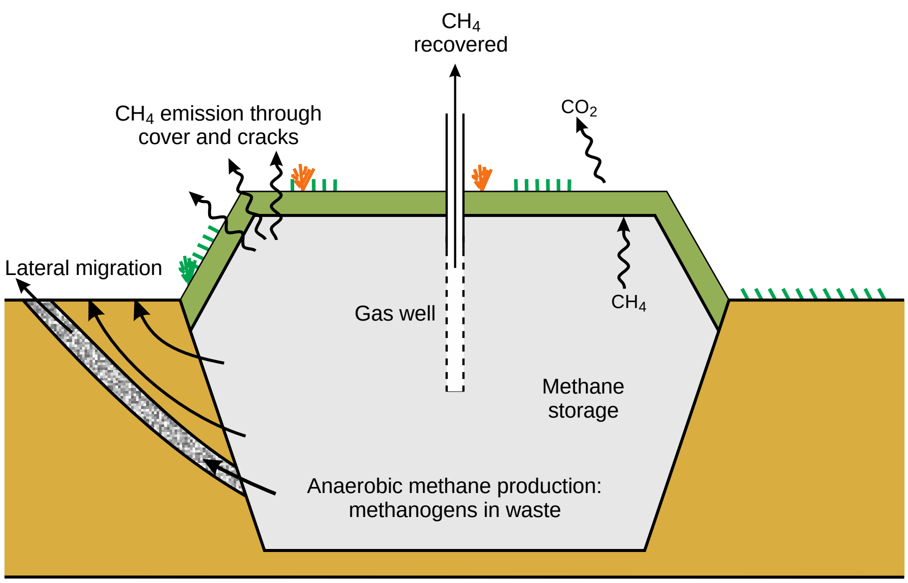

Figure 1- Methane production, transport, and emission from a landfill. [1]

Site Background and History

Sunshine Canyon Landfill (Class III landfill) operates under Solid Waste Facility Permit 19-AA-2000 issued by CalRecycle located in Sylmar, California. The site is owned and operated by Browning Ferris Industries of California, Inc./Republic Services, Inc. The "County Landfill" Disposal Phases I through V are located north of the City-County boundary, and were constructed with a composite liner and leachate collection and removal system. The "City Landfill" includes Unit 1 and Unit 2 waste disposal areas that are south of the City-County boundary. City Landfill Unit 1 is a closed, unlined Class III MSW disposal unit that operated between 1958 and

1993. City Landfill Unit 2 is currently active, Class III MSW disposal unit that was constructed with a composite liner system and is located generally between City Landfill Unit 1 and the County disposal phases. Cell A of City Landfill Unit 2 began operations during the third quarter of 2005, with subsequent disposal operations expanding into Cells CC-1 and CC-2. Refuse is currently being disposed of in Cell CC-3A (See Appendix A, Figure A1-SCL Proposed Phasing Plan). The maximum weekly tonnage received at the facility is 66,000 tons of municipal solid waste (MSW) for disposal and 6,600 tons of material received for beneficial reuse and recycling, which together total 72,600 tons per week for all material. Currently the landfill receives 8,300 tons of MSW per day. The permitted maximum elevation of the waste is 1,904 ft. (MSL) on portions within the “County Landfill” boundary and 2,004 ft. (MSL) on portions within the “City Landfill”. The total permitted area for waste disposal is 363 acres with design capacity of 140,900,000 cubic yards of MSW. The site is estimated to close by 2037.

Since 2009, the members of communities surrounding the Sunshine Canyon Landfill (SCL) have reported smelling odors to SCAQMD and SCL (See Figure 2). In response to the complaints, SCAQMD staff sought an Order for Abatement from its autonomous Hearing Board. The Hearing Board issued an Order for Abatement that requires a number of activities designed to reduce potential odors from the landfill, such as installation of additional gas wells and flares; limiting landfilling under certain wind conditions at certain times of day; implementing new restrictions at the working face; enhancing odor patrols; rerouting transfer trucks on Monday mornings; and replanting lost vegetation that may help with the dispersion of odors. To date Republic Services has engaged in a variety of studies aimed at better understanding the sources of potential odors from the SCL, the possible transport of odors from SCL to the community, and potential odor-reduction measures. Republic Services has implemented numerous odor control measures and has hired consultants to evaluate the immediate and future needs of LFG collection and disposal systems to accommodate the capture and destruction of all gas expected to be generated at the landfill using vertical landfill gas wells, horizontal collectors, liner collectors, trench collectors, and flares.

In March 2010, the SCAQMD issued a stipulated order for Abatement followed by three stipulated Amended orders for Abatement that imposed a series of conditions including making enhancements to the LFG collection system to address odor nuisance. In addition, the County of Los Angeles, Public Works Department required corrective measures be implemented by Republic Services to reduce odors. Republic Services was required to cover disposed solid waste with a minimum of 9-inches of compacted soil at the end of each operating day in lieu of using tarp or other alternative daily cover. Republic Services was also required to discontinue removal of the daily cover at the beginning of the next operating day. In spite of these operational changes that have taken place during the past four years, odor complaints continue but the number of complaints has decrease recently. Data on the number of complaints reported to SCAQMD between 1995 and 2015 is shown in Figure 2.

In October 22, 2014, the County of Los Angles Public Works Department required Republic Services to implement additional corrective measures to mitigate the odor nuisance resulting from activities related to the operation of the SCL. The LFG management requirements were as follows: a) newly completed cells shall have three vertical gas extraction wells per acre and horizontal collectors are every other lift. For cells that will be inactive for more than two days horizontal gas collectors must be installed within the top lift; b) At a minimum for each existing and future development cell calculate the in-place density of fill material taking into account the daily soil cover, and calculate the radius of influence as well as spacing for vertical gas extraction wells and horizontal gas collectors based on that density. Areas with different site characteristics may require separate calculations of in-place densities. These calculations and well spacing must be submitted to Public Works for approval with copies to SCAQMD and SCL Local Enforcement Agency (LEA).

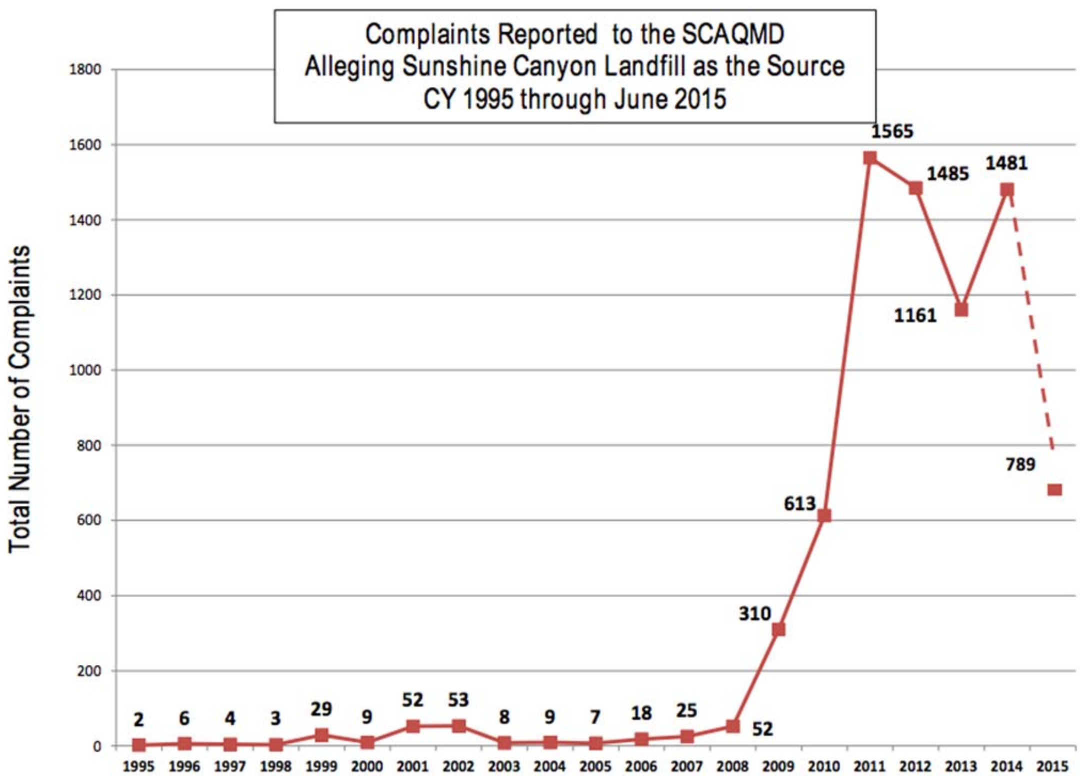

Figure 2- Total number of complaints reported to the SCAQMD between 1995 to 2015 (Figure provide by SCAQMD).

Studies Conducted at SCL to Mitigate Landfill Odor

Addressing various operations and design issues can reduce landfill odor in the surrounding area of a landfill (Figure 3). These issues are: a) reducing the working face of the landfill and application of daily cover material; b) timely application of final cover and vegetation layer; c) properly sized LFG collection and control system; d) odor-neutralizing chemical sprayed along the border; e) proper maintenance of leachate and LFG control equipment components; f) surface water management and proper grading of the landfill surface to reduce water infiltration; g) using the gas as a fuel to reduce odors and provide electricity.

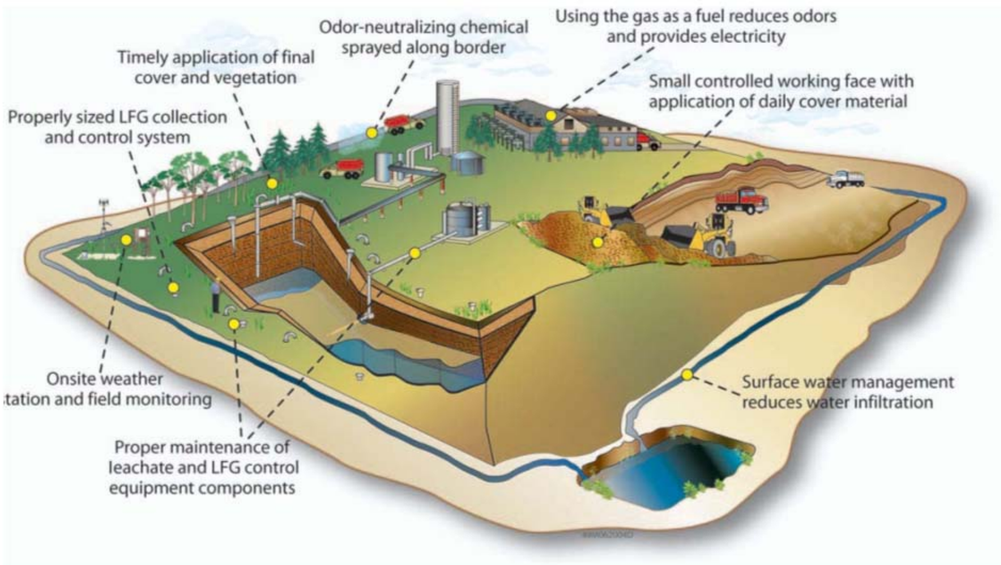

Figure 3- Typical landfill with various systems to control odor.[2]

Studies that have been conducted at SCL to better identify the cause and to better manage odor at the SCL landfill are listed below. Some of the recommendations identified in these studies have already been implemented.

In 2011 a study was conducted by ENVIRON International Corporation[3] to evaluate the impact of landfill working face size and rate of waste deposited on odor. Based on the data collected it appeared that odor source strength at the working face did not correlate with working face size. Also, the chemical measurements as well as olfactory observations did not indicate any apparent trends when compared to working face size and odor complains received from the hotlines.

In 2011 Tetra Tech BAS (BAS)[4] evaluated the existing landfill gas collection and control system and recommended changes to increase the current landfill gas collection efficiency. BAS used the October 4, 2010 LFG generation analysis prepared by Cornerstone Environmental Group, LLC as the primary reference for an independent analysis. Cornerstone's report referenced several waste composition studies performed for the SCL. In February 2015, Tetra Tech, Inc. and EcoTelesis International[5] performed a more recent waste characterization study performed to develop better parameters for the landfill gas models used at the SCL. According to this study the total readily degradable wet fraction of organic waste (food waste) was determined to be beween 23% to 30%.

In 2011, landfill gas collection improvement recommendations by BAS were: a) installation of additional 70 vertical gas wells in the areas with the most surface emissions; b) installation of a temporary flare with a 3,000 SCFM capacity; c) replacement of flare#8 with a larger capacity flare; d) evaluation for improvement of flare station #1 and #3; e) replacement of the undersized gas collection and control system piping. Many of these recommendations have already been implemented at the SCL.

In 2012, a white paper was prepared by Blue Ridge Services[6] to evaluate and determine the most effective means to prevent off-site odor from the active face of the landfill. Blue Ridge Services evaluated the effectiveness of the required nine (9) inches of daily soil cover as a mitigation measure for reduction of off-site odors as compared to the regulatory standard six (6) inches of` soil. Other site conditions that have historically contributed to the off-site odor problem were also evaluated. The recommendation of this study was to discontinue placement of nine (9) inches of daily cover soil and instead use Alternative Daily Cover (ADC). Additionally, it was pointed out that the use of nine (9) inches of daily cover soil could impede the vertical movement of leachate and landfill gas and cause lateral migration. See Appendix A, Figure A2, for the boundary of the nine (9) inches of daily soil cover and the location of vertical gas wells with dedicated pumps for dewatering gas wells.

Methods for Estimation of Landfill Gas Generation Rate

There are several methods to estimate LFG generation rate: a) a first-order kinetic gas generation model such as the Landfill Gas Emission Model (LandGEM) (USEPA 2005[7]); b) combination of pneumatic well test data with assumptions about well recovery to estimate LFG generation (EMCON 1980[8]); c) and biokinetic models describing stages of waste decomposition (El-Fadel et al. 1996[9]). These methods have significant limitations when estimating the actual LFG generation. The default CH_4 generation potential, L_0, and first-order waste decay rate, k, recommended in LandGEM model are dependent on site conditions (Scharff and Jacobs 2006[10]) and even when site specific L_0 are used errors can significantly affect estimates of k (Tolaymat et al. 2010[11]). Additionally, estimates require assumptions about the LFG collection efficiency, which are also unknown.

In another recent study[12], the observed methane collection data from 11 U.S. landfills and estimates of gas collection efficiencies developed from site-specific gas well installation data were included in a reformulated LandGEM equation. The results demonstrated that the current LandGEM model (AP-42) default decay rate used by industry is too low. This is significant because a higher decay rate will result in predictions of more methane generation in the early years after waste burial when gas collection efficiencies tend to be lower. Thus higher decay rates will result in higher estimates of uncollected methane. This research also suggests that it is misleading to refer to L_0 as the methane production potential because the value of L_0 in LandGEM includes unmodeled parameters that influence methane generation. Further work is required to identify the controlling unmodeled parameters, explore reformulations of LandGEM that might include a slow and rapidly decomposing waste fraction, quantify uncertainty, and expand observational data sets.

The baro-pneumatic method (Bentley et al. 2003[13]) used by HGC in the most recent study at the SCL quantified LFG generation rates and estimated the field gas permeability within the landfill using simultaneous measurement of gas pressure at the surface and at various landfill depths. The mathematical analyses of pressure changes in the refuse in response to variation in atmospheric pressure, LFG generation, and pumpage at LFG extraction well were used to make the estimate. The baro-pneumatic method uses site-specific data that reduce uncertainties in estimated of LFG generation rates. This method does not assume that the LFG generation rate is equal to the flow rate of a gas extraction well within its zone of influence, an assumption that is technically flawed (Walter 2003[14]) and therefore the baro-pneumatic method is a better method to quantify LFG generation rates.

Photo 1- Shallow and deep vapor monitoring wells with pressure transducers installed.

In 2014, SCAQMD hired Hydro Geo Chem, Inc. (HGC)[15] to perform field tests and collect atmospheric and subsurface pressure data within the landfill and analyze the collected data both qualitatively and quantitatively to make recommendation for potential solutions to control odor from the landfill. Three locations were selected for this field study. Two locations were selected in the newer portion of the landfill near collector well CGW740 S/D and CGW575 and the third location in the older portion of the City landfill near the collector well GW7024 (See Appendix A, Figure A3). After the well monitoring installation, HGC installed a series of pressure transducers for monitoring pressures within the landfill at these three locations (Photo 1).

At location CGW740 S/D results demonstrate that cover material (approximately 1.5 feet thick at this location) provides only a slight barrier to pneumatic communication between the atmosphere and the subsurface, consistent with its thinness and a moderately high vertical permeability. The results also suggest that the vertical permeability of at least the shallowest refuse (between 1.5 feet and 8 feet in depth) is relatively high. The apparent poor communication of deep refuse with the atmosphere suggests that the deep refuse has a low gas permeability or that partial pneumatic barriers exist in the refuse at depths greater than approximately 35 feet bls, possibly the result of layers having high water contents and low gas porosity. Overall, the LFG collection system appears to be effective at this location except in the deep refuse where pressures are greater than atmospheric and at distances greater than 75 feet from CGW740 S/D where LFG control system induced vacuums were slight.

At location CGW575, the cover material is approximately 6 feet thick and provides a barrier to pneumatic communication between the atmosphere and the subsurface. The apparent poor communication of deeper refuse (> 95 ft. bls) with the atmosphere suggests that at least partial pneumatic barriers exist in the refuse.

At location GW7024, the cover material thickness is approximately 10 feet thick and the data suggest that cover soil has higher effective gas permeability than cover at CGW575.

The results above indicate that the cover soil permeability may be too high or soil may not be compacted enough, allowing gas emission. Comparing this with the published soil survey[16] for the SCL (Figure 4 and Figure 5), the majority of the soils at the SCL are rated to have a moderately high-saturated hydraulic conductivity. There is not a clear proportionality between high-saturated hydraulic conductivity and porosity. However, typically sandy soil with high porosity will have a high hydraulic conductivity (more open areas for flow of water or gas), but this relationship is more complicated in soils with clay. <u>We recommend the collection of in-tact core samples of cover soil at various locations at the SCL for laboratory testing. These samples will be sent to the University of Delaware laboratories where density, total porosity and gas transport properties will be measured. While the initial water content of the samples will be recorded, the effect of moisture on gas transport will be evaluated by varying the water content systematically in each sample in the laboratory. We can provide a detail proposal for further study at a later date.</u>

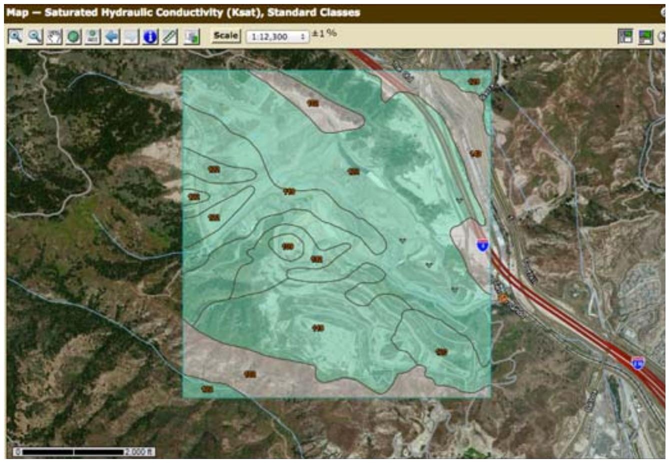

Figure 4- Map of standard classes of soil at SCL.[16]

Tables — Saturated Hydraulic Conductivity (Ksat), Standard Classes — Summary By Map Unit

Summary by Map Unit — Los Angeles County, California, West San Fernando Valley Area (CA676)

Map unit symbol	Map unit name	Rating (micrometers per second)	Acres in AOI	Percent of AOI
102	Badland		96.4	10.7%
109	Chualar-Urban land complex, 2 to 9 percent slopes	4.3989	6.3	0.7%
119	Gazos silty clay loam, 30 to 50 percent slopes	2.7000	223.8	24.8%
120	Gazos-Balcom complex, 30 to 50 percent slopes	2.7000	41.9	4.7%
122	Millsholm loam, 30 to 50 percent slopes	9.0000	424.7	47.1%
129	Saugus loam, 30 to 50 percent slopes	9.0000	10.7	1.2%
132	Soper gravelly sandy loam, 15 to 30 percent slopes	4.9329	30.3	3.4%
143	Xerorthents-Urban land-Saugus complex, 15 to 30 percent slopes		67.2	7.5%
Totals for Area of Interest			**901.3**	**100.0%**

Description — Saturated Hydraulic Conductivity (Ksat), Standard Classes

Saturated hydraulic conductivity (Ksat) refers to the ease with which pores in a saturated soil transmit water. The estimates are expressed in terms of micrometers per second. They are based on soil characteristics observed in the field, particularly structure, porosity, and texture. Saturated hydraulic conductivity is considered in the design of soil drainage systems and septic tank absorption fields.

For each soil layer, this attribute is actually recorded as three separate values in the database. A low value and a high value indicate the range of this attribute for the soil component. A "representative" value indicates the expected value of this attribute for the component. For this soil property, only the representative value is used.

The numeric Ksat values have been grouped according to standard Ksat class limits. The classes are:

Very low: 0.00 to 0.01
Low: 0.01 to 0.1
Moderately low: 0.1 to 1.0
Moderately high: 1 to 10
High: 10 to 100
Very high: 100 to 705

Figure 5- Saturated hydraulic conductivity of soils at SCL.[16]

Impact of Barometric Pressure Change on Landfill Methane Emission and Automated Landfill Gas Well Adjustment

In a number of studies the influences of atmospheric pressure on landfill methane emissions have been evaluated. The diurnal measurement during a drop in barometric pressure show that LFG fluxes can change dramatically within a very short time (Czpiel et al., 2003[17]; Giani et al., 2002[18]; Christophersen, et al., 2001[19]; Xu et al., 2014[20]). For example, in one study by Czepiel, et al. 2003[21] conducted at the Nashua, New Hampshire municipal landfill, with an active vertical and horizontal gas collection system, found surface methane fluxes increased 300% due to decreases in barometric pressure of 10 millibars, which occurred during passage of low pressure weather fronts over an anaerobic landfill (Figure 6). In another landfill study with passive gas collection system a 35-fold variation in day-to-day methane emissions was observed due to changes in barometric pressure (Figure 6). Rising barometric pressure suppressed the emission, while falling barometric pressure enhanced the emission, a phenomenon called barometric pumping (Xu et al., 2014[20]). Generally speaking, high pressure (usually dry air) is associated with calm, sunny weather and low pressure (generally moist air) occurs on cloudy, rainy days.

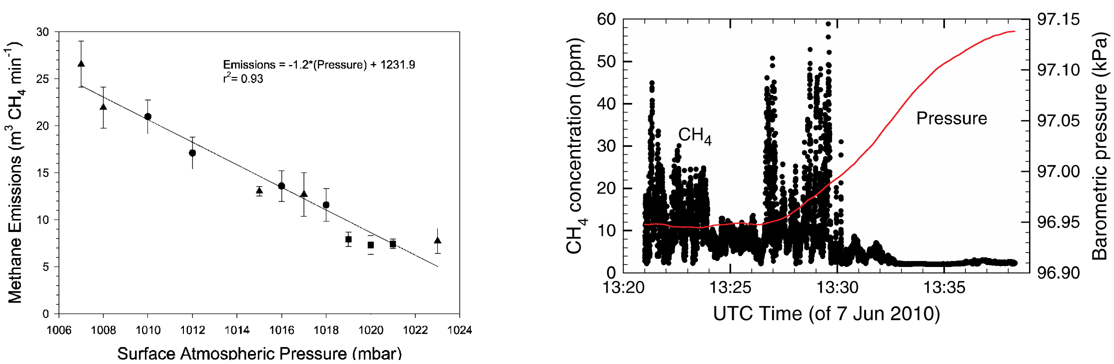

Figure 6- Results from two studies showing increase in methane emissions over a short time as barometric pressure drops[17,20].

As demonstrated in Figure 7 and Figure 8, the atmospheric pressure at the SCL changes on a daily or even hourly basis, as well as seasonally. This is due to normal day and night cycle of solar radiation, and also due to local weather patterns. SCAQMD Rule 1150.1 requires quarterly landfill emissions monitoring by walking the surface of the landfill and scanning for methane emissions (at this site monthly emissions monitoring is performed). Typically surface emission monitoring is not performed during falling barometric pressure (bad weather such as wind greater than 5 mph and/or rainy weather) when the surface emissions could be higher. Landfill surface scanning is normally performed during the day when the weather is calm and the barometric pressure is high. This could underestimate the actual average daily emission measured by surface scanning method. If the barometric pressure drops during the night, emission flux and odor from the landfill increase. Current air emission regulations ignore the barometric pressure impacts and assume that surface emission is constant under high or low atmospheric pressure in landfills with active or passive LFG collection system. In order to prevent excess emission and odor from the landfill each wellhead must be under continuous monitoring and automatically adjusted as the barometric pressure changes. This is not typically done and is not even required by regulations; however, this type of landfill gas operation may reduce emissions and therefore odor from the landfill. Such a system was designed, tested and successfully operated at the Yolo County Central landfill as part of a research project for the California Energy Commission[22]. A commercial version of such system has recently been developed by Loci Controls[23] and in the summer of 2014 was tested at the Crapo Hill Landfill in Dartmouth, Massachusetts. Using automation to control each gas wellhead increased the power output from the LFG to energy facility by 26% at this landfill site, and therefore reduced the overall landfill gas surface emissions. Photos 2 and 3 show the typical control software screen used for automatic adjustment of the gas wellhead and the wellhead construction at the landfill, respectively. We recommended that such a system be tested at the SCL on a main header line where series of LFG wells are connected together and on one LFG well. Automatic adjustment of individual gas wells is ideal but automatic adjusting of the main header line with series of gas wells connected together could also improve fugitive gas emissions. Gas collection system should be tested under various operating parameters such as wellhead suction and gas composition to determine the effectiveness of system and reduction of fugitive gas emissions and air intrusion. We can provide a detail proposal for further study at a later date.

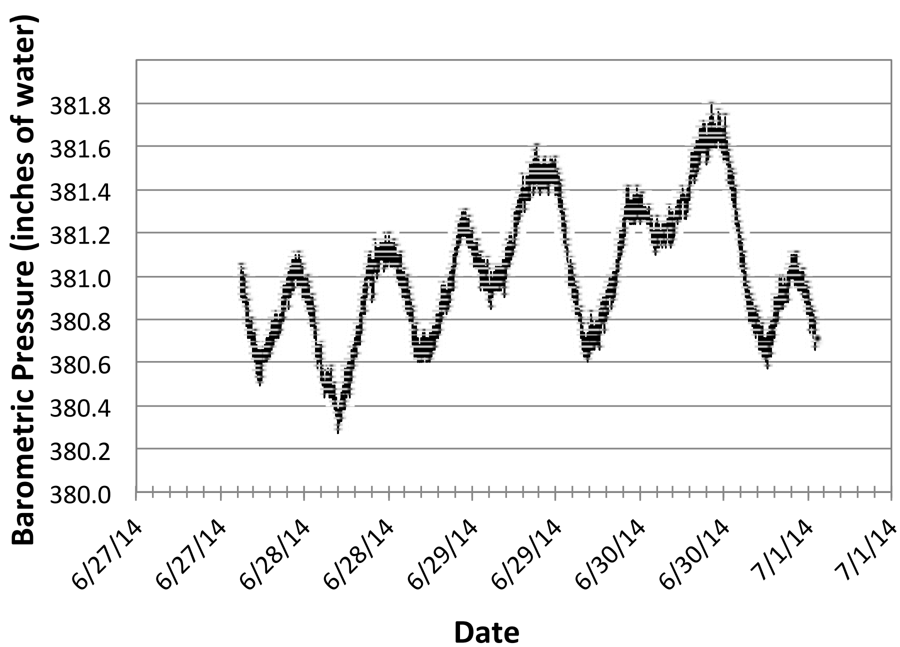

Figure 7- Barometric pressure at Sunshine Canyon Landfill during pneumatic test (data from HGC pneumatic field test-June 27- July 1, 2015).

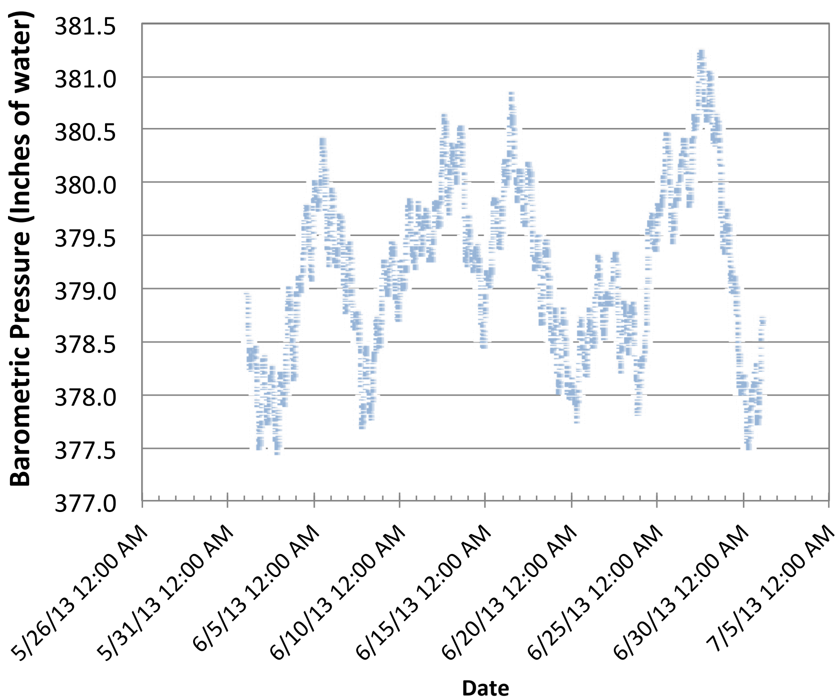

Figure 8- Sunshine Canyon Landfill Weather Station Barometric Pressure Data for June 2013.

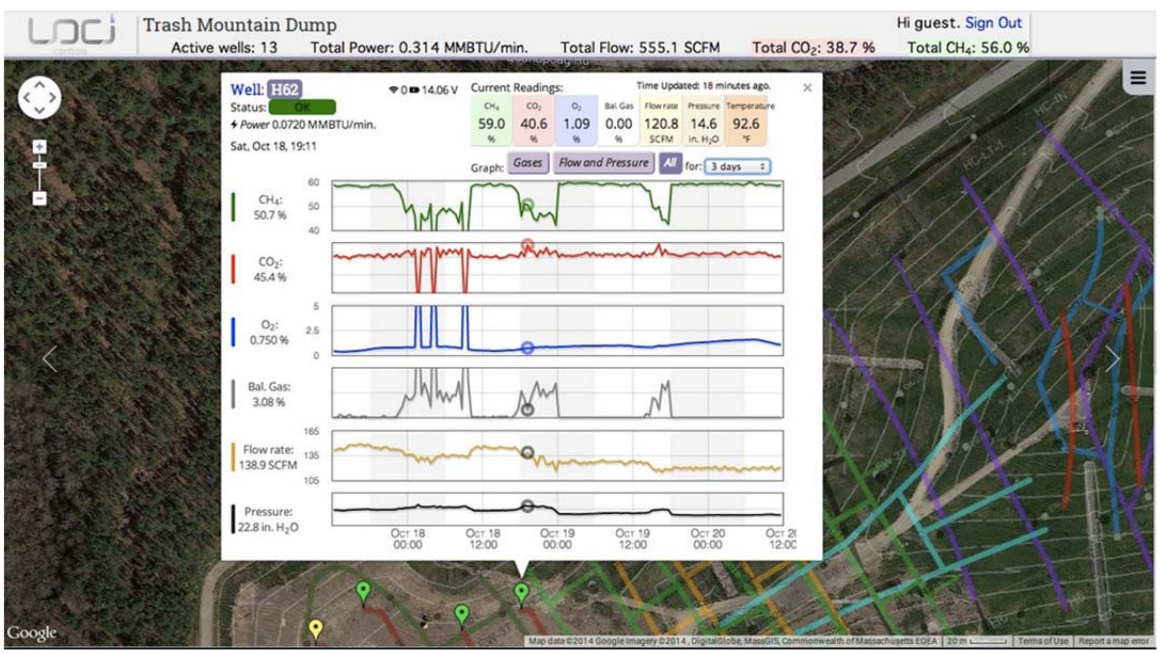

Photo 2- Loci Controls WellWatcher monitoring software used to automatically monitor each gas well.

Photo 3- Loci Controls WellWatcher monitoring & control system used to automatically adjust and monitor each landfill gas well.

Landfill Gas Collection Efficiency Measurement Using Gas Tracers

When designing a LFG collection system, an assessment of the region of influence (ROI) of each well in required. A simple way to assess the ROI of a pumping well is to measure the gas pressure distribution in the refuse with the well on and off. If there is a measurable difference in gas pressure at any sampling point between the on/off conditions, then this point is impacted by the well. The ROI is affected by the LFG generation rate, which can vary in space and time; waste compaction and moisture content; the extraction rate at individual wells; the locations of wells in the landfill; and the degree to which gas can permeate the landfill boundaries. Understanding where LFG collection is "good" and where it is "poor" is the first step to developing improved designs for gas collection systems.

Currently we are only aware of one study where direct measurements LFG collection efficiency was made using an in-situ gas tracer method (Yazdani et al., 2015[24]). The gas tracer method was used to quantify gas collection efficiencies at various points in a test landfill well and results were compared with the ROI as determined from pressure measurements. While an assessment of a well's ROI might result in specified steady-state suctions applied at well-heads to achieve optimal collection efficiency, transient LFG flow results from barometric pressure variations can significantly impact collection efficiency. As discussed earlier, published literature indicates that barometric pressure changes result in undesired "pulses" of LFG emissions to the atmosphere similar to what has been observed at the SCL during early morning and late afternoon as indicated by the Blue Ridge Services[6] report and other studies (Kjeldsen and Fischer 1995[25]; Borjesson and Svensson 1997[26]; Christophersen, Kjeldsen et al. 2001[27]; Czepiel, Shorter et al. 2003[28]). In addition, over-pressure LFG building within isolated areas of the landfill could also cause release of LFG. Thus, a LFG collection system that is manually adjusted on a weekly or monthly basis without consideration of atmospheric pressure changes or internal pressure within the landfill may result in appreciable fugitive methane emissions as well as air intrusion. Imhoff et al., 2012[24] performed computer simulations and have conducted large-scale field tests that supports this observation. As illustrated in Figure 9(a), two variations in atmospheric pressure are shown: a moderate case, where 24-hour average barometric pressure data from Sacramento, California collected for a one-month period were used; and a strong case, where variations in atmospheric pressures measured at the Skellingsted Landfill, Denmark (Poulsen, Christophersen et al. 2003[29]) were selected. The resulting LFG emissions predicted from this LFG model (Jung, Imhoff et al. 2009[30]) are shown in Figure 9(b). For two cases: one with a permeable layer installed near the landfill surface to enhance LFG capture and one without. In both cases, the gas collection well was operating such that a constant mass flux of LFG was extracted from the landfill. While the existence of a near-surface permeable layer decreased baseline methane emissions from 22 to 15% of the methane generated in the landfill, barometric pressure changes still resulted in emission spikes. It is important to note that these simulations had no "cracks" in the landfill cover and the soil type was not highly permeable: cracking and permeable cover soil would allow significantly greater fugitive emissions in response to barometric changes, with effects approaching those cited in Czepiel's study (Czepiel et al., 2003[28]). As suggested earlier, we recommend that an automated wellhead adjustment be used to mitigate the influence of atmospheric pressure changes on the operation of LFG collection systems and emissions. This type of operation will result in reduced emissions, increased collection efficiency, and the costs associated with such a system may be offset by the increased revenue potential from the additional LFG collected and energy produced at the existing LFG to energy facility.

We recommend that the in-situ gas tracer method developed by Yazdani et al., 2015[24] be used to determine the vertical gas well collection efficiency and to assess alternative gas collection strategies and landfill cover system (intermediate and final cover) to mitigate the effects of barometric pressure changes and various cover system designs used to control LFG emissions.

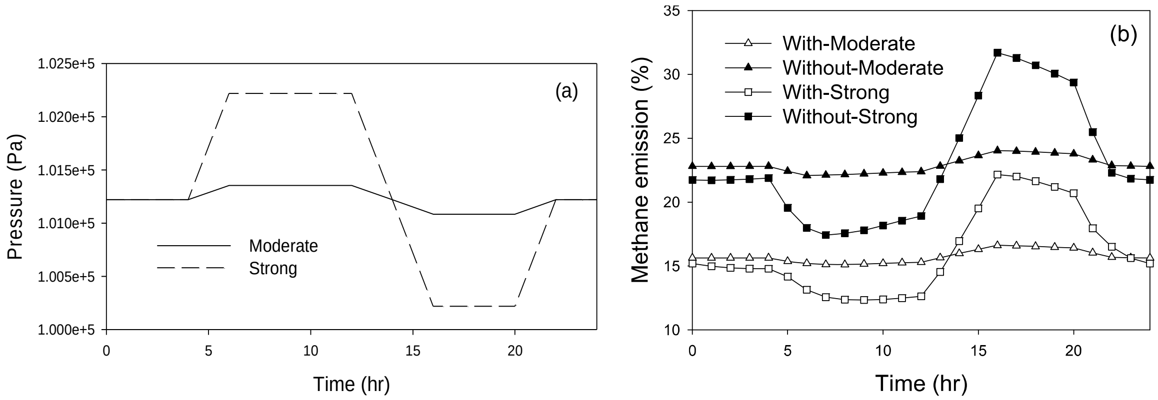

Figure 9- Variations in methane emissions associated with atmospheric pressure changes over a 24-hour period (Jung, Imhoff et al. 2009[30]). Results are shown for a landfill with or without a horizontal permeable layer installed at the top of the landfill. (a) Variations in atmospheric pressure; (b) variations in methane emissions, expressed as % of total methane generated in refuse.

Better Landfill Gas Collection System Design to Mitigate Emissions and Air Intrusion in Landfill

Typically vacuum is applied to LFG collection wells to pull gas out of the waste in landfill via vertical extraction wells or horizontal extraction trenches. Figure 10 (a) illustrates the direction and magnitude of the expected gas flows with arrows drawn. Pumping of the vertical gas collection wells may cause unequal methane emissions and air intrusion at the landfill surface. To address this problem an alternative LFG collection system design is proposed for the SCL as shown in Figure 10 (b) (Augenstein et al., U.S. Patent No. 7,198,433 (2007)[31], Jung, et al. 2011[32]). In this new landfill gas collection system design, a high-permeability layer is installed near the landfill surface and LFG is collected at deep pumping wells (not from the high-permeable layer near the surface). This enables essentially uniform pressure across the entirety of the conductive or permeable layer, and can enable a uniform vertical pressure gradient through the surface layers of the landfill and greatly reduce irregularities in vertical gas flow at the landfill surface. In other words, it will greatly reduce the air entrainment near vertical wells, and fugitive emission far from vertical wells, as shown in Figure 11. The expectation is better efficiency of gas collection because a high permeability layer equalizes differences in gas pressure near the landfill surface resulting in: 1) reduced methane emissions through cover materials and; 2) more uniform flow of LFG through landfill covers; and 3) reduction in the extent of air intrusion.

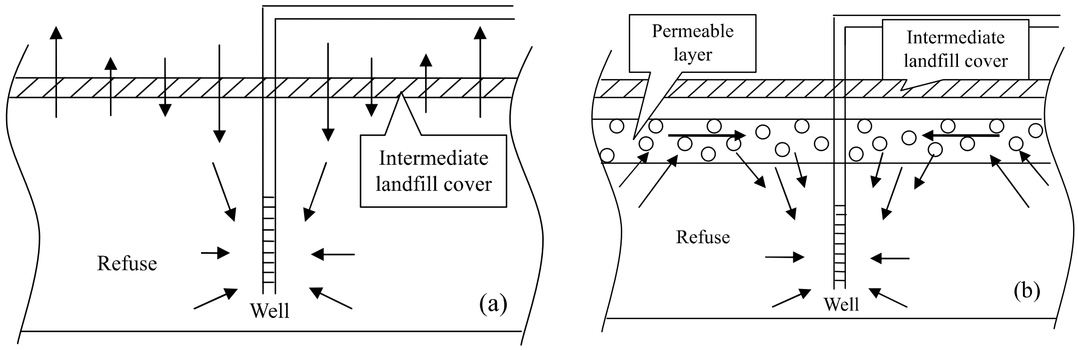

Figure 10- Typical cross-section of gas collection system: (a) conventional vertical landfill gas collection well; (b) landfill gas collection well with permeable layer.

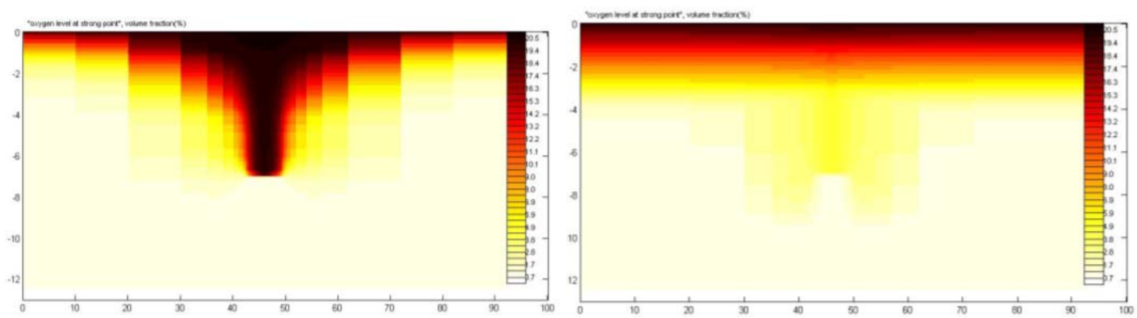

Figure 11- Oxygen profiles (% by mass) for conventional vertical landfill gas collection well (left) and landfill gas collection well with permeable layer (right).

This type of design is also applicable where for areas with intermediate cover and waste has not reached the final elevation and additional waste will be placed on top of existing waste lift (Figure 12). Permeable layer can be constructed from waste material that is three to five orders of magnitude more permeable than the surrounding waste such as shredded tires (used only in areas where waste oxidization is not a concern), gravel, and C&D waste. However, the intermediate cover soil material must be less permeable than the waste below. This design will also minimize atmospheric air intrusion into landfill gas collection system, a problem that is currently seen in the SCL gas system. Figure 13 shows landfill gas balance and oxygen data for all of the vertical gas wells (not including City-South area) at the SCL (between 2/4/2014 to 7/24/2015) for the past two years (12,487 recorded vertical gas wellhead composition data collected). During this time, 368 vertical gas wells out of 410 (89.8% of the vertical gas wells) had LFG balance content (nitrogen gas) equal to or greater than of 20%(v/v), and 95 vertical gas wells out of 410 (23.2% of the vertical gas wells) had oxygen content equal to or greater than 5% (v/v). This indicates that many of the landfill gas wells are pulling air into the landfill. This creates an oxidizing environment in the landfill that leads to consumption of methane by oxidation and could increase the risk of landfill fire.

We also recommend that gas samples from the main LFG collection system in these areas be tested for carbon monoxide (CO) levels using laboratory instrument (gas chromatography) and not measured using field instrument because of interference with other gases present. We also recommend the proposed permeable layer LFG collection system design be tested in a section of the landfill (intermediate or final fill area) to determine how it might be implemented to reduce gas emissions at the SCL. Further assistance in the design and testing of such system can be provided. We can provide a detail proposal for further study at a later date.

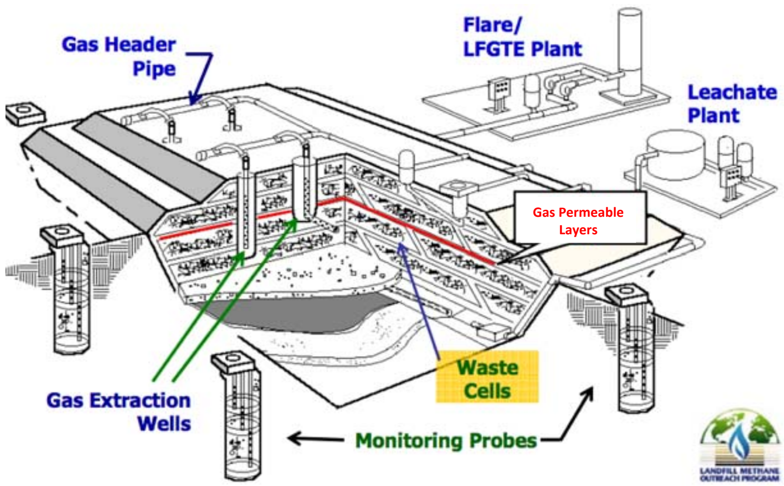

Figure 12- Landfill gas collection well with permeable layer installed as waste filling advances.

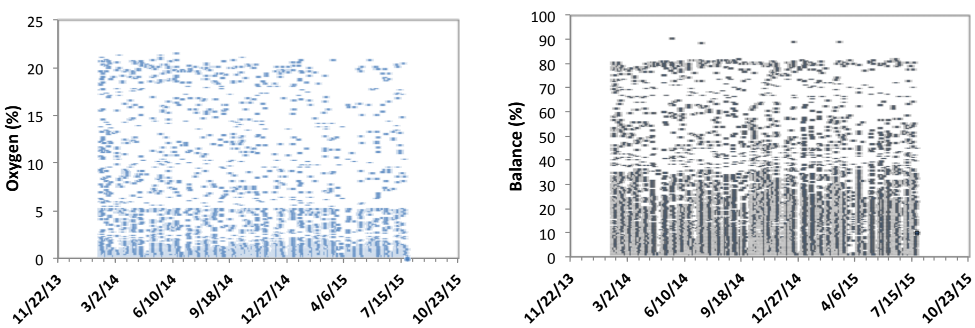

Figure 13- SCL vertical landfill gas well data between 2/4/2014 to 7/24/2015.

Saturated Waste Condition and Gas Collection Efficiency

Waste that is saturated with water can greatly reduce gas permeability (Jain et al., 2005[33]; Reinhart et al., 2002[34]). Liquid movement and change in water saturation may also be affected by refuse heterogeneity (McCreanor and Reinhart, 2000[35]). In a landfill simulation study by Jung, et al., 2011[32] the mean gas permeability of waste was reduced by a factor of five while all other parameters remained the same. Modeling results showed that without the near-surface permeable layer the conventional landfill gas design had emissions that were 25% of the total CH_4 generated. This indicates that conventional LFG collection systems are not efficient where gas permeabilities are reduced because of elevated moisture conditions (Jain et al., 2005[33]), conditions that appear to exist in the lower layers of waste at the SCL. After installation of dewatering wells and trenches, the near-surface permeable layer design extends the zone of influence of the pumping well and causes a more uniform vertical LFG flow above the permeable layer and results in near constant collection efficiencies of biogas regardless of variations in heterogeneous landfill conditions, including variations in gas permeability (Jung et al., 2011[32]). We recommend that dewatering trenches be installed and the new landfill gas collection design be tested in a section of the landfill with saturated condition with intermediate cover to determine how it may be implemented to reduce gas emissions and improve gas collection efficiency. Further assistance in the design and testing of such system can be provided at a later date. We can provide a detail proposal for further study.

Hydrogen Sulfide Production in Landfills and the Use of Soil as Daily Cover

In landfill environments where there is an absence of oxygen (anaerobic condition), microbes degrade organic waste and produce carbon dioxide (CO_2) and methane (CH_4), typically produced in equal quantities (Eq. 1). When sulfur is present, it is converted by anaerobic bacteria to H_2S. Typically sulfur is present in the form of sulfate (SO_4) but also in the form of elemental sulfur (S) and sulfite (SO_3).

$$\text{Organic matter (e.g. municipal waste)} + H_2O \rightarrow CO_2 + CH_4 \quad \text{Eq. (1)}$$

$$\text{Organic matter (e.g. municipal waste)} + SO_4 + H_2O \rightarrow H_2S + CO_2 \quad \text{Eq. (2)}$$

In order for H_2S to be produced in landfill environment, as shown in Eq. 2 above, two ingredients are needed, a source of organic matter and source of sulfur (S). Organic matter is present in the form of municipal or commercial waste, biosolids or leachate in liquid form. The sulfur (S) can be present in construction and demolition (C&D) waste (wallboard), the wallboard fines from a material recover facility (MRF) that processes C&D waste, fly ash or other industrial waste containing sulfur. Also, sulfur could be present in the soil used as daily cover at the landfill site.

In 2011, soil samples from several soil stockpiles at the SCL were tested for various chemical properties. Laboratory results were reported in the geological and geotechnical investigation report prepared by AMEC, 2011[36]. Based on the test results by AMEC the average sulfate content of soil used as daily cover was 1,424 mg/kg. Each year about 700,000 to 1,000,000 cubic yards of soil is used as daily and intermediate cover soil at the SCL. Calculation based on the average sulfate content of the cover soil indicates that around 1,500 to 2,100 tons of sulfate is added to the landfill annually. This has the potential of producing over 500 to 750 tons of H_2S. The use of daily and intermediate cover soil with high levels of sulfate could increase the potential for odors. We recommend that samples of the soil used for daily and intermediate cover be tested for sulfur content. Samples should also be tested for biochemical sulfur potential (BSP) in an anaerobic environment to determine the potential of soil producing H_2S. The North Carolina State University laboratory is the only one we are aware of that is qualified to perform BSP tests on soil samples. A proposal can be provided for laboratory testing of soil to determine the sulfur content and the BSP.

Control of Emissions at the Active Filling Area

In addition to the recommendations made for alternative daily cover (ADC) to control emissions at the active filling area by HGC[15], other ADC material such as compost[37] and shredded green waste[38] have shown to be an effective means of controlling LFG emissions and should be considered for further testing at the SCL instead of nine (9) inches of cover soil. The use of green waste as ADC may be limited due to local City and/or County policy of diverting green waste from the landfill as well as mandatory waste diversion assembly bill (AB 1826 and AB 341). Other studies have also investigated bio-tarp[39] as an alternative cover to reduce emission that may be considered instead. In addition to recommendations made by HGC to use spray on products as daily cover, we recommend investigating the possibility of obtaining shredded green waste or compost that could also be used as ADC. We also suggest investigating the use of bio-tarp as an alternative cover to reduce emission.

Impact of Daily Cover Soil Use on Landfill Gas Transport and Emission

In order to better assess the impact of nine (9) inches of daily cover on landfill gas transport and emission, analysis of the effects of daily cover on gas transport properties and water retention is needed. We recommend two methods to further gather data. In the first method, we propose the collection of in-tact waste core samples at various depths at the SCL using sonic drilling technique (Figure 14) in conjunction with freezing of samples (to maintain pore structure). The eight (8) inch diameter samples that are continuously lined with plastic tubes will be used to collect waste samples at depths and in locations with little or no significant daily cover. These samples will be sent to the University of Delaware laboratories where density, total porosity and gas transport properties will be measured. While the initial water content of the samples will be recorded, the effect of moisture on gas transport will be evaluated by varying the water content systematically in each sample in the laboratory. The University of Delaware has conducted similar measurements on other waste samples (Han et al., 2011)[40]. This information will quantify the effect of daily cover on water retention and gas transport properties, information that may be used in numerical modeling of landfill gas transport and emissions in the SCL. In the second method, we propose to use in-situ cone penetration test (CPT) and piezocone penetration test (PCPT) (Figure 15). This is a fast, economical method that provides continuous profiling of waste to determine various conditions such as: location of compacted waste and cover soil layers, liquid and gas pressures, identify zones of vacuum, determine density of waste as a function of depth (Figure 16). We recommend that a study be conducted to get a better understand of how the soil layers used as daily cover impacts gas and water movement in landfill. We can provide a detailed proposal for further study at a later date.

Figure 14- Waste sampling using a Sonic drilling unit

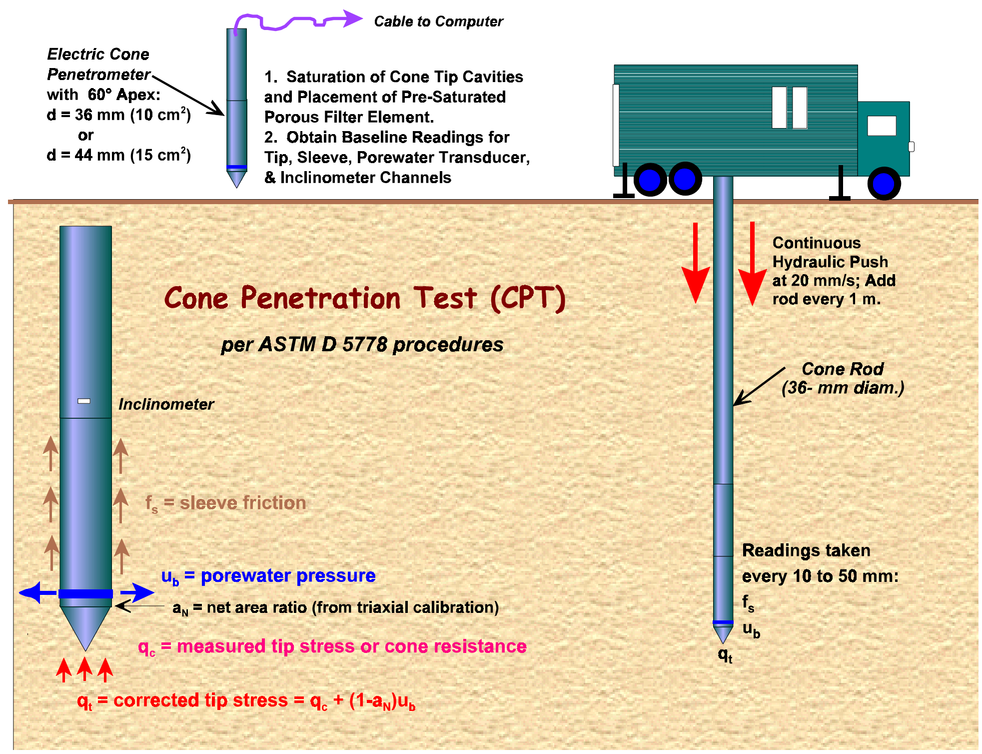

Figure 15- Cone Penetration Test (CPT) procedure and setup[41].

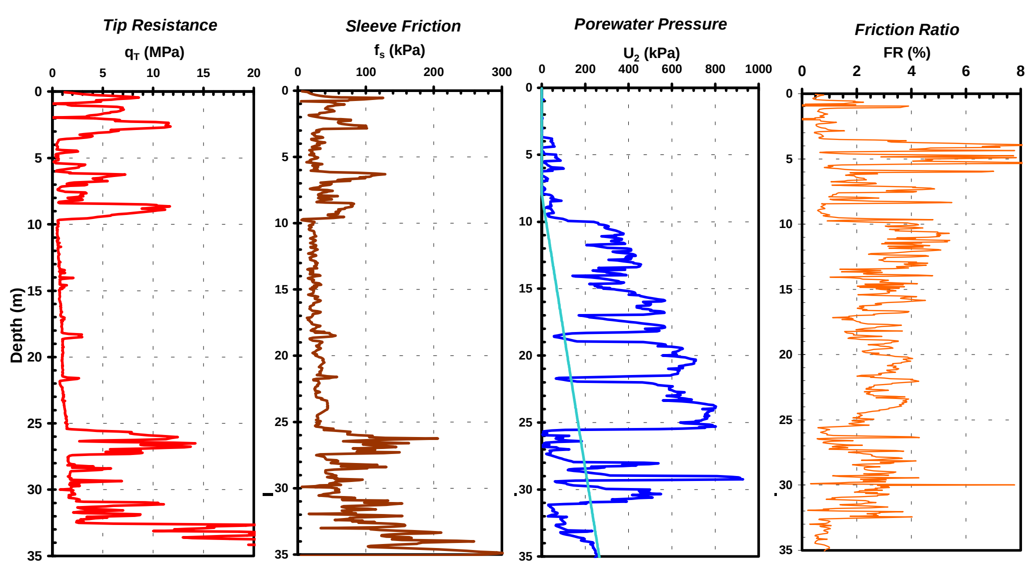

Figure 16-Typical Piezocone Cone Penetration (PCPT) test results[41].

Measurement of Whole-Landfill Gas Emissions

In Southern California, the main anthropogenic emission sources of CH_4 are landfills (Table 1)[42]. There are several field methods to measure landfill CH_4 emissions such as static and dynamic flux chamber methods at ground level, subsurface concentration and pressure gradient methods, and above ground micrometeorological and tracer methods (Scheutz et al., 2009)[43]. Entire landfill emissions could be measured (dynamic or stationary) using a tracer-dilution method, where downwind concentration of emission mixed with the reference gas tracer released (Figure 17) is measured (Galle et al., 2001[44]; Czepiel et al., 1996[45]; Trégourès et al., 1999[46]). Such methods have recently been tested and evaluated for landfill emission quantification (Babilotte, 2011[47]; Goldsmith et al., 2012[48]; Green et al., 2010[49]; Peischl et al., 2013 [50]).

California Air Resources Board (ARB) owns a mobile measurement platform (MMP) with equipment to measure greenhouse gas emissions (e.g., nitrous oxide (N_2O,)-tracer gas, methane (CH_4), and carbon dioxide (CO_2)) and is currently in use in the Los Angeles area. We recommend that an entire landfill emission measurement (dynamic or stationary) using a tracer-dilution method be conducted. We recognize that applying this method to this site could be challenging but it will provide more insight to better understand the source of odors. We propose to coordinate with ARB in order to conduct whole landfill emissions testing using the tracer-dilution method. If ARB is unable to assist then we propose to coordinate with either Los Gatos Research (LGR) located in Mountain View, California or Picarro in Santa Clara, California. Picarro conducted similar preliminary tests of such mobile setup at the Yolo County Central Landfill. Both companies have developed portable instruments to measure GHG with low detection limits needed for such emissions study.

Table 1- CARB Year 2004 statewide and South Coast Air Basin (SoCAB) portion of LA County CH_4 inventories.[42]

Sector	Statewide emissions[a]	SoCAB portion of LA County emissions[a]	Major sources
Agriculture & forestry	0.81	0.06	Rice cultivation[b]
Fuel combustion	1.0	0.21	Transportation
Fugitive emissions	2.6	0.01	Natural gas pipelines
Wastewater treatment	2.8	0.77	
Landfills	5.6	1.9	
Livestock	13	0	Dairy and beef cows[b]
Total	26	3.0	

Data Source – California Greenhouse Gas Emissions Inventory (CARB, 2008a).
[a] MMT CO_2 E $year^{-1}$.
[b] There is no known rice cultivation or dairy activities in LA County.

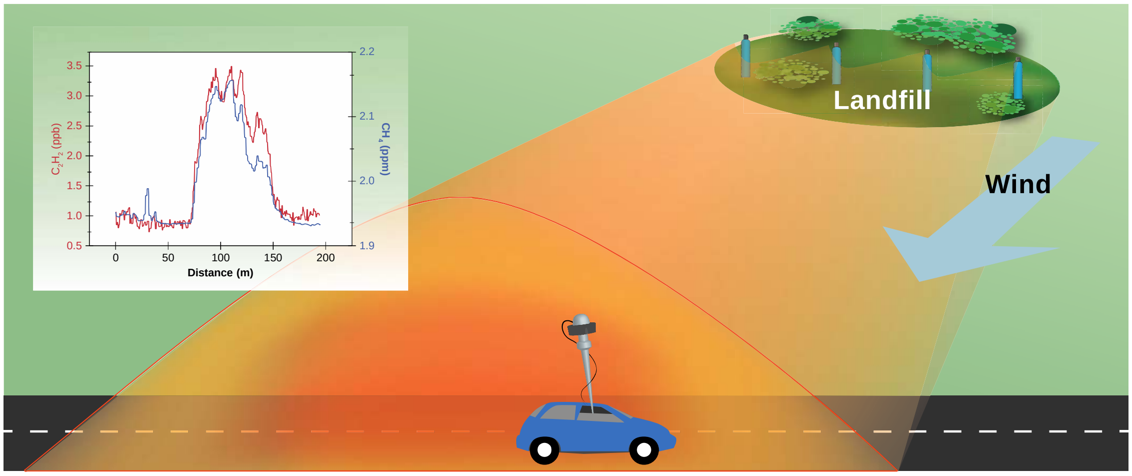

Figure 17- Schematic view of dynamic dispersion method applied at a landfill.[1]

Summary of Recommendations:

In addition to the recommendations in the HGC report[15] we recommend the following:

1) **Intermediate Cover Soil Testing**- We recommend the collection of in-tact core samples of cover soil at various locations (top and side slopes) at the SCL to better understand the properties of the on-site soil. These samples will be sent to the University of Delaware laboratories where density, total porosity and gas transport properties will be measured. While the initial water content of the samples will be recorded, the effect of moisture on gas transport will be evaluated by varying the water content systematically in each sample in the laboratory. These parameters can directly impact the amount of LFG released to the atmosphere through the cover soil and therefore increase the potential odor at the SCL.

2) **Daily Cover Soil**- The following tests related to the use of daily cover soil are recommended:
   a) We recommend that representative samples of daily cover soil stockpile be collected and tested for sulfur content. Samples should also be tested for biochemical sulfur potential (BSP) under anaerobic environment to determine its potential for production of H_2S. These tests will be sent to North Carolina State University for laboratory testing.
   b) Samples of the landfill leachate from various leachate collection areas of the landfill should also be tested for sulfate.
   c) Landfill gas samples from various locations (gas wells and gas header lines) should be collected for H_2S laboratory testing.

d) We also recommend two types of field studies to gather data and better understand how the daily cover soil layers impact gas and water movement in landfill and the impact it has on gas collection efficiency and emissions.
   i) In the first study, we propose the collection of in-tact core samples of waste at various depths using sonic drilling technique in conjunction with freezing of samples (to maintain pore structure). These samples will be sent to the University of Delaware laboratories where density, total porosity, and gas transport properties will be measured. While the initial water content of the samples will be recorded, the effect of moisture on gas transport will be evaluated by varying the water content systematically in each sample in the laboratory. This information will quantify the effect of daily cover on water retention and gas transport properties, information that may be used in numerical modeling of landfill gas transport and emissions in the SCL.
   ii) In the second study, we propose to use in-situ cone penetration test (CPT) and piezocone penetration test (PCPT). This is a fast, economical method that provides continuous profiling of waste to determine various conditions such as: location of compacted waste and cover soil layers, liquid and gas pressures, identify zones of vacuum, and determine density of waste as a function of depth.

3) **Alternative Daily Cover (ADC)**- As suggested by HGC[15] other types of ADC (spray on products) should be used instead of the on-site soil, particularly because of high sulfate content of soil that could react with leachate generated. In addition to spray on products, we recommend investigating the possibility of obtaining shredded green waste or compost that could be used as ADC. The use of green waste as ADC may be limited due to local City and/or County policy of diverting green waste from the landfill as well as mandatory waste diversion assembly bills (AB 1826 and AB 341). We also suggest investigating the use of bio-tarp[51] as ADC to reduce emission.

4) **Estimation of LFG Generation Rate and LFG Collection Adjustment**-
   a) We recommend using the baro-pneumatic method to estimating LFG generation because it reduces uncertainties in estimation of LFG generation rates.
   b) The current method of LFG wellhead adjustment entrains air into the landfill and does not take into account the diurnal barometric pressure changes. We recommend that at least one main header line with several gas wells and one gas well in the area where baro-pneumatic tests were performed by HGC be modified with an automatic wellhead adjustment system (Loci Controls[23]). To determine the effectiveness of reducing landfill gas emissions we recommend gas tracer method[24] be used to measure the actual gas collection efficiency with and without the automatic wellhead adjustment system.

5) **Saturated Waste Condition and Gas Collection Efficiency**- We recommend that the near-surface permeable layer [31] be designed, constructed, and tested in an area where waste is saturated and surface emissions are known to be a problem. The gas collection efficiency will be measured before and after installation of this permeable layer using the gas tracer method[24].

6) **Whole-Landfill Gas Emissions**- We recommend using the tracer-dilution method (dynamic or stationary) to conduct several weeks of field study to determine the entire landfill emissions under different atmospheric conditions. Results will be used to identify the location of gas emissions within the SCL site.

Appendix A

Figure A1-SCL Joint Technical Document (JTD) 2007, Proposed Phasing Plan

Figure A2- SCL Location of Vertical Gas Wells with Dedicated Pump and Boundary of nine (9) inch Daily Soil Cover

Figure A3-Hydro Geo Chem, Inc. Field Test Location at the SCL

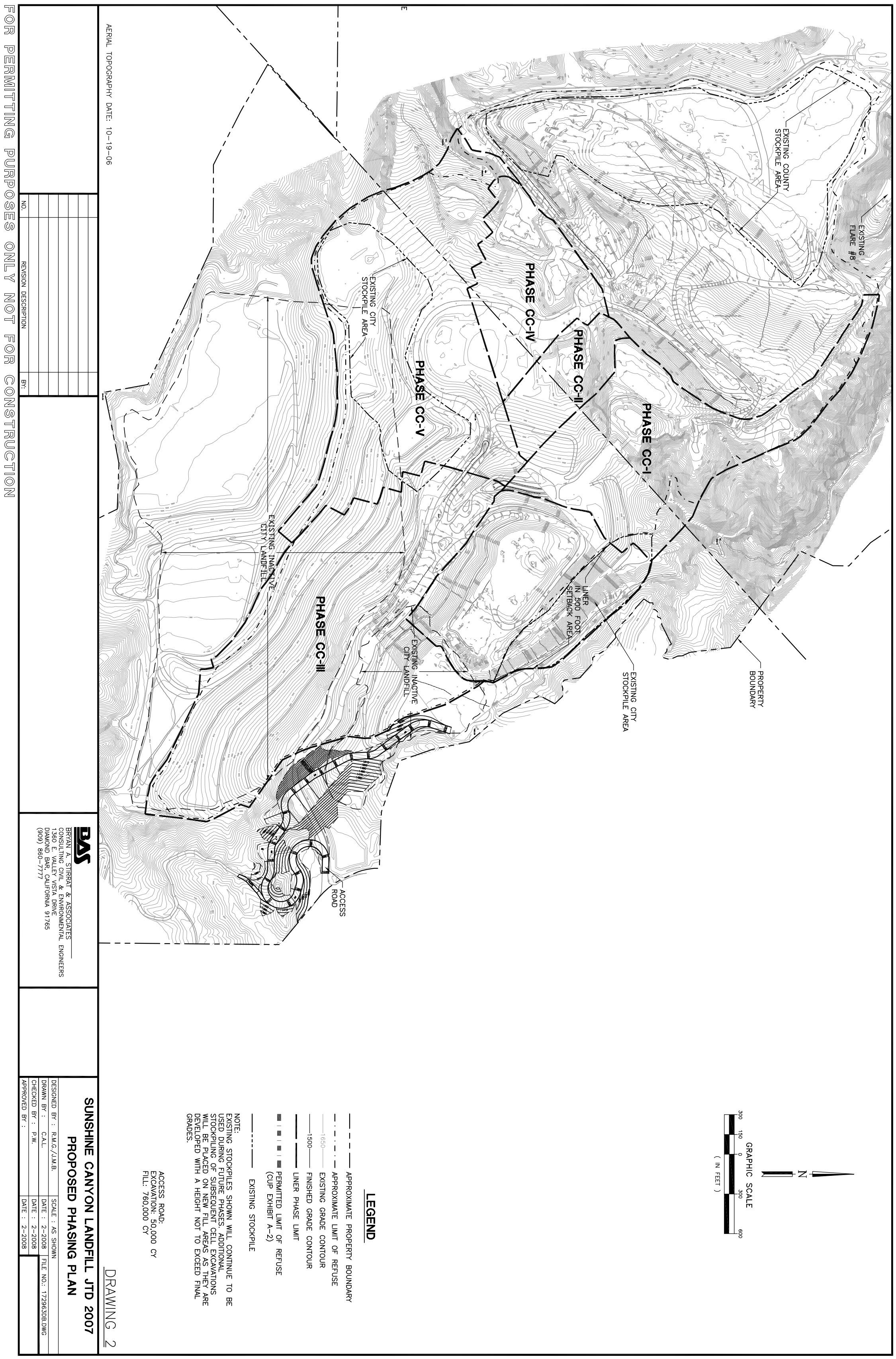
FOR PERMITTING PURPOSES ONLY NOT FOR CONSTRUCTION
AERIAL TOPOGRAPHY DATE: 10-19-06
PHASE CC-I
PHASE CC-II
PHASE CC-III
PHASE CC-IV
PHASE CC-V
EXISTING COUNTY STOCKPILE AREA
EXISTING FLARE #8
EXISTING CITY STOCKPILE AREA
EXISTING INACTIVE CITY LANDFILL
LINER IN 500 FOOT SETBACK AREA
PROPERTY BOUNDARY
ACCESS ROAD
BRYAN A. STIRRAT & ASSOCIATES
CONSULTING CIVIL & ENVIRONMENTAL ENGINEERS
1360 E. VALLEY VISTA DRIVE
DIAMOND BAR, CALIFORNIA 91765
(909) 860-7777
NO.
REVISION DESCRIPTION
BY:
LEGEND
APPROXIMATE PROPERTY BOUNDARY
APPROXIMATE LIMIT OF REFUSE
EXISTING GRADE CONTOUR
FINISHED GRADE CONTOUR
LINER PHASE LIMIT
PERMITTED LIMIT OF REFUSE (CUP EXHIBIT A-2)
EXISTING STOCKPILE
NOTE:
EXISTING STOCKPILES SHOWN WILL CONTINUE TO BE USED DURING FUTURE PHASES. ADDITIONAL STOCKPILING OF SUBSEQUENT CELL EXCAVATIONS WILL BE PLACED ON NEW FILL AREAS AS THEY ARE DEVELOPED WITH A HEIGHT NOT TO EXCEED FINAL GRADES.
ACCESS ROAD:
EXCAVATION: 50,000 CY
FILL: 760,000 CY
GRAPHIC SCALE
(IN FEET)
DRAWING 2
SUNSHINE CANYON LANDFILL JTD 2007
PROPOSED PHASING PLAN

Figure A1

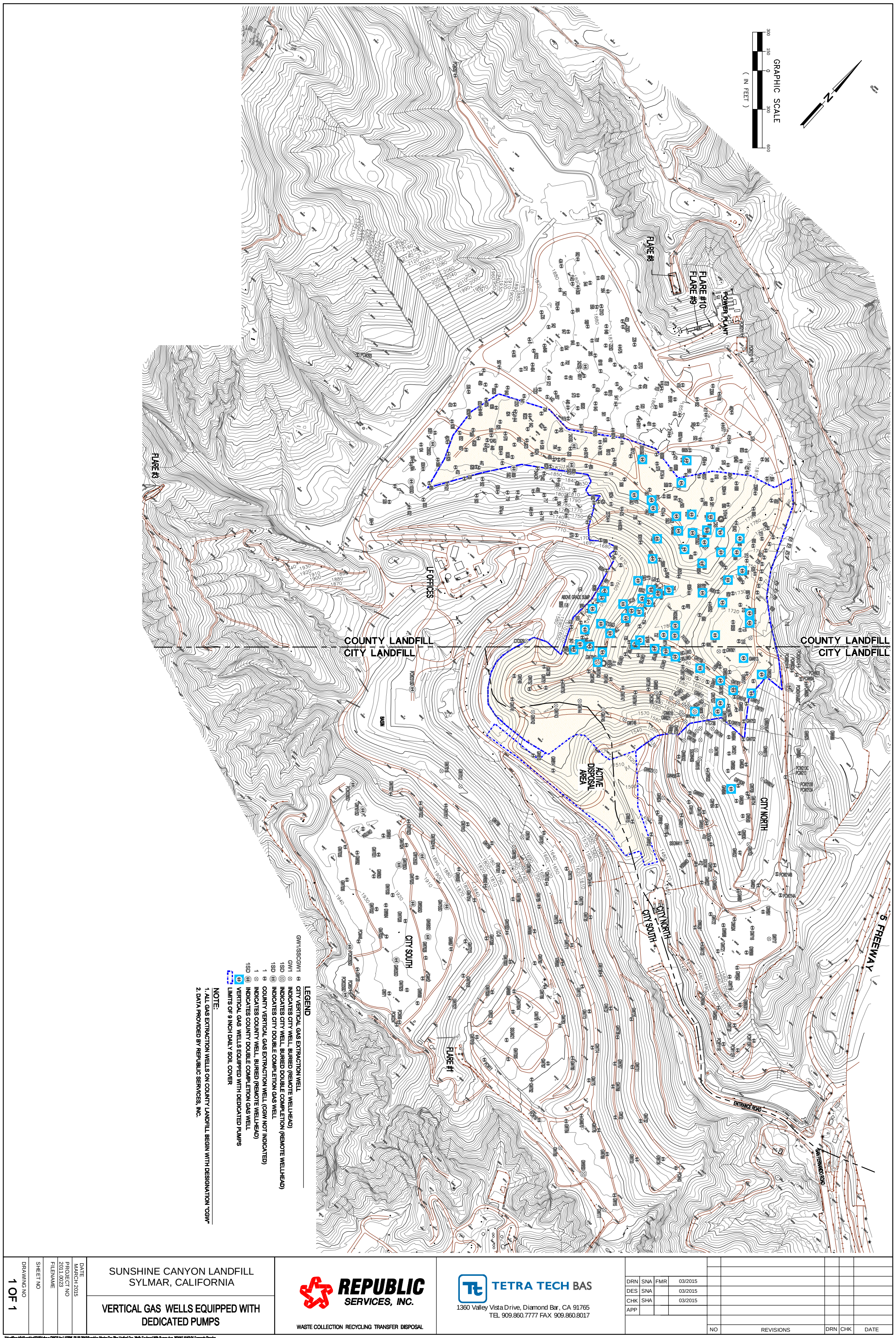
GRAPHIC SCALE
(IN FEET)
FLARE #3
FLARE #9
FLARE #10
FLARE #8
POWER PLANT
LF OFFICES
COUNTY LANDFILL
CITY LANDFILL
ACTIVE DISPOSAL AREA
CITY NORTH
CITY SOUTH
FLARE #1
5 FREEWAY
ENTRANCE ROAD
LEGEND
NOTE:
SUNSHINE CANYON LANDFILL
SYLMAR, CALIFORNIA
VERTICAL GAS WELLS EQUIPPED WITH DEDICATED PUMPS
REPUBLIC SERVICES, INC.
WASTE COLLECTION RECYCLING TRANSFER DISPOSAL
TETRA TECH BAS
1360 Valley Vista Drive, Diamond Bar, CA 91765
TEL 909.860.7777 FAX 909.860.8017
DRAWING NO
1 OF 1
REVISIONS

Figure A2

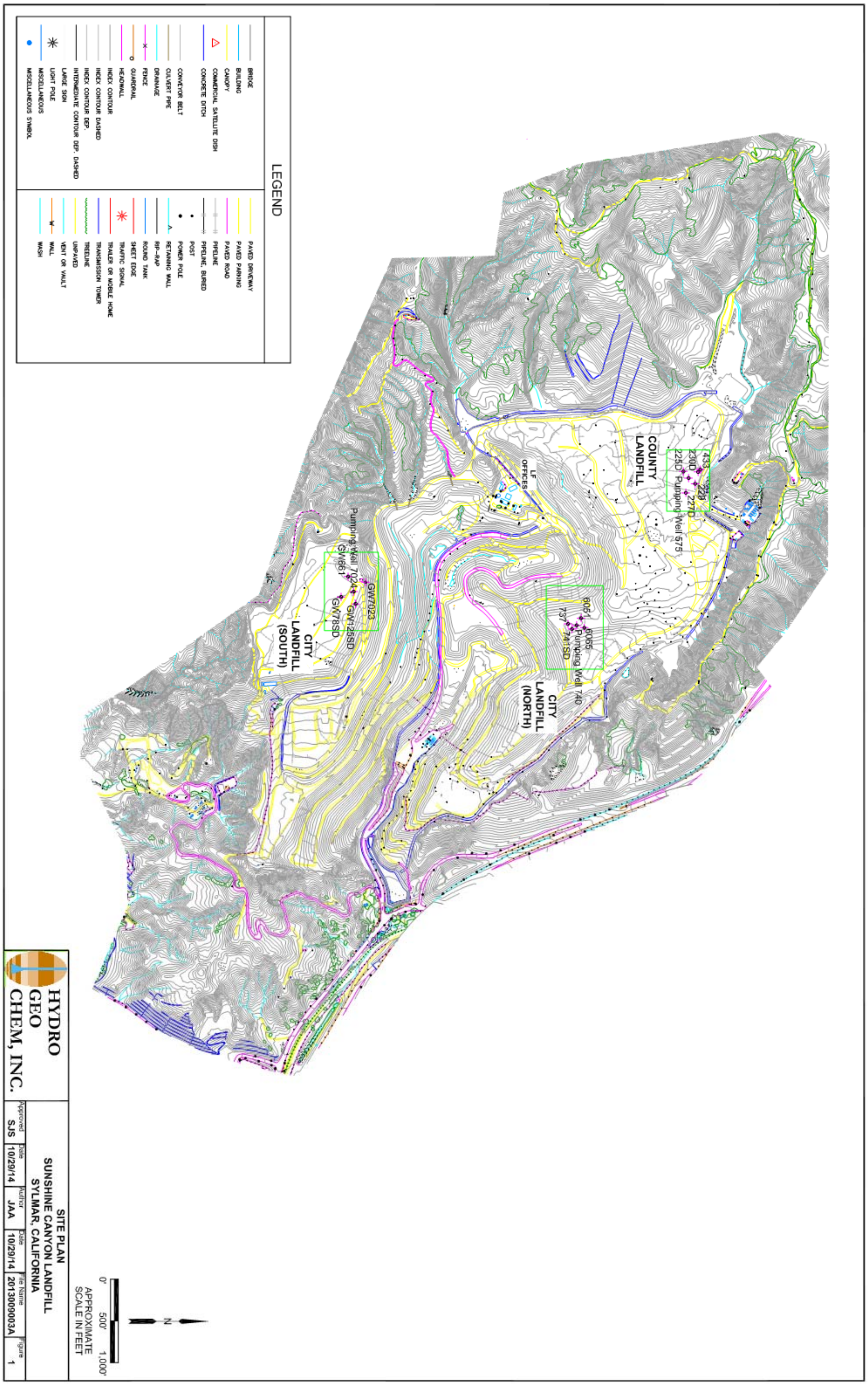
LEGEND
COUNTY LANDFILL
LF OFFICES
CITY LANDFILL (NORTH)
CITY LANDFILL (SOUTH)
HYDRO GEO CHEM, INC.
SITE PLAN
SUNSHINE CANYON LANDFILL
SYLMAR, CALIFORNIA
APPROXIMATE SCALE IN FEET

Figure A3

Limitations

No investigation is thorough enough to guarantee the future elimination of odor at the SCL site. While this report provides reasonable recommendations and suggests further studies to improve odor control at SCL, it should not be construed as a guarantee that the suggested ideas would accurately forecast the elimination of odor at the SCL site.

The services described in this report were performed consistent with generally accepted professional consulting principles and practices. No other warranty, express or implied, is made. These services were performed consistent with our agreement with you, our client. This report is solely for the use and information of our client unless otherwise noted. Any reliance on this report by a third party is at such party's sole risk.

Opinion and recommendations contained in this report apply to conditions existing when services were performed and are intended only for the client, purposes, locations, time frames and project parameters indicated. We are not responsible for the impacts to any changes in environmental standards, practices, or regulations subsequent to performance of services. We do not warrant the accuracy of information supplied by others, or the use of segregated portions of this report.

List of References

[1] Jacob Mønster, (2014)"Quantifying greenhouse gas emissions from waste treatment facilities." PhD Thesis, DTU Environment, Department of Environmental Engineering, Technical University of Denmark.

[2] Managing Solid Waste Facilities to Prevent Odor", National Solid Wastes Management Association (NSWMA).

[3] "*Working Face Study Sunshine Canyon Landfill Sylmar, California",* ENVIRON International Corporation, June 14, 2011.

[4] "*Sunshine Canyon Landfill Evaluation of the Existing Landfill Gas Collection and Control System",* Tetra Tech BAS, November 29, 2011.

[5] *"Sunshine Canyon Landfill Supplemental Waste Characterization Study "*, Tetra Tech, Inc. and EcoTelesis International, May, 2015.

[6] "*Assessment of Alternative Daily Cover Related to Origin and Control of Landfill Odor",* Blue Ridge Services, December 18, 2012.

[7] USEPA: Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide. EPA-600/R-05/047 (2005).

[8] EMCON: Methane Generation and Recovery from Landfills. Ann Arbor Science Publishers, Ann Arbor (1980).

[9] El-Fadel, M., Findikakis, A.N., Leckie, J.O. "Numerical modeling of generation and transport of gas and heat in landfills I. Model formulation." Waste Manag. Res. 14, 483–504 (1996).

[10] Scharff, H., Jacobs, J. "Applying guidance for methane emission estimation for landfills." Waste Manag. 26, 417– 429 (2006).

[11] Tolaymat, T.M., Green, R.B., Hater, G.R., Barlaz, M.A., Black, P., Bronson, D., Powell, J. "Evaluation of landfill gas decay constant for municipal solid waste landfills operated as bioreactors." J. Air Waste Manag. Assoc. 60, 91–97 (2010).

[12] Wang, X., Nagpure, A. S., DeCarolis, J. F., Barlaz, M. A. " Using Observed Data to Improve Estimated Methane Collection from Select U.S. Landfills." Environ. Sci. Technol., 2013, 47 (7):3251–3257.

[13] Bentley, H.W., Smith, S.J., Tang, J., Walter, G.R. "A method for estimating the rate of landfill gas generation by measurement and analysis of barometric pressure waves." In: Proceedings of the 18th International Conference on Solid Waste Technology and Management, Philadelphia, PA (2003).

[14] Walter, G.R. "Fatal flaws in measuring landfill gas generation rates by empirical well testing." J. Air Waste Manag. Assoc. 53, 461–468 (2003).

[15] "*Pneumatic Testing and Recommended Changes at the Sunshine Canyon Landfill*", Hydro Geo Chem, Inc., March 11, 2015.

[16] http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/ref/?cid=nrcs142p2_053573

[17] Czepiel, P.M., Shorter, J.H., Mosher, B., Allwine, E., McManus, J.B., Harriss, R.C., Kolb, C.E., Lamb. B.K. (2003). " The influence of atmospheric pressure on landfill methane emissions." Water Management 23(7):593-598.

[18] Giani, L., J. Bredenkamp, et al. (2002). "Temporal and spatial variability of the CH4 dynamics of landfill cover soils."J. Plant Nutr. Soil Sci., 165, 205–210.

[19] Christophersen, M., Kjeldsen, P., Holst, H., Chanton, J. (2001). " Lateral gas transport in soil adjacent to an old landfill: factors governing emissions and methane oxidation." Waste Manag. Res. 19(6):595-612.

[20]Xu, L., Lin, X., et al. (2014). "Impact of changes in barometric pressure on landfill methane emission." Global Biogeochemical Cycles 28 (7): 679–695.

[21]Czepiel, P. M., J. H. Shorter, et al. (2003). "The influence of atmospheric pressure on landfill methane emissions." Waste Management 23(7): 593-598.

[22] Yazdani, R., D. Augenstein, P. Imhoff, M. Barlaz. (2008), "Demonstration of Landfill Technology for Peaking Power Potential at Yolo County Central Landfill." California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-00-034.

[23] http://locicontrols.com

[24] Yazdani, R., Imhoff, P.T., Han, B., Mei, C., Augenstein, D. (2015). "Quantifying Capture Efficiency of Gas Collection Wells with Gas Tracers", Waste Management, 43: 319-327.

[25] Kjeldsen, P. and E. V. Fischer (1995). "Landfill Gas Migration - Field Investigations at Skellingsted Landfill, Denmark." Waste Management & Research 13(5): 467-484.

[26] Borjesson, G. and B. H. Svensson (1997). "Seasonal and diurnal methane emissions from a landfill and their regulation by methane oxidation." Waste Management & Research 15(1): 33-54.
[27] Christophersen, M., P. Kjeldsen, et al. (2001). "Lateral gas transport in soil adjacent to an old landfill: factors governing emissions and methane oxidation." Waste Management & Research 19(6): 595-612.

[28] Czepiel, P. M., J. H. Shorter, et al. (2003). "The influence of atmospheric pressure on landfill methane emissions." Waste Management 23(7): 593-598.

[29] Poulsen, T. G., M. Christophersen, et al. (2003). "Relating landfill gas emissions to atmospheric pressure using numerical modeling and state-space analysis." Waste Management & Research 21(4): 356-366.

[30] Jung, Y. J., P. T. Imhoff, et al. (2009). "Influence of high-permeability layers for enhancing landfill gas capture and reducing fugitive methane emissions from landfills." Journal of Environmental Engineering-ASCE 135(3): 138-146.

[31] Augenstein, D. C., Benemann, J. R., Yazdani, R., "Landfill Design and Method for Improved Landfill Gas Capture". U.S. Patent No. 7,198,433 (2007).

[32] Jung, U., Imhoff, P.T., Augenstein, D., Yazdani, R. (2011). " Mitigating methane emissions and air intrusion in heterogeneous landfills with a high permeability layer". Waste Management 31(5):1049-1058.

[33] Jain, P., Powell, J., Townsend, T.G., Reinhart, D.R., (2005). "Air permeability of waste in a municipal solid waste landfill." J. Environ. Eng. 131 (11), 1565–1573.

[34] Reinhart, D.R., McCreanor, P.T., Townsend, T.G., (2002). "The bioreactor landfill: its status and future." Waste Manage. Res. 20, 172–186.

[35] McCreanor, P.T., Reinhart, D.R., (2000). "Mathematical modeling of leachate routing in a leachate recirculating landfill." Water Res. 34 (4), 1285–1295.

[36] "Geologic and Geotechnical Investigation Report for Sunshine Gas Producers Landfill Gas to Energy Project at Sunshine Canyon Landfill", prepared by AMEC for HR Green, Inc., November 15, 2011.

[37] Scheutz, C., Pedersen, R. B., Petersen, P. H., Jørgensen, J. H. B., Ucendo, I. M. B., Mønster, G. M., Samuelsson, J., Kjeldsen, P. (2014). "Mitigation of methane emission from an old unlined landfill in Klintholm, Denmark using a passive biocover system.", Waste Management, 34 (7): 1179-1190.

[38] Mei, C., Yazdani, R., Han, B., Mostafid, M.E., Chanton, J., VanderGheynst, J., Imhoff, P. (2015). " Performance of green waste biocovers for enhancing methane oxidization.", Waste Management, 39(1):205-215.
[39] Adams, B.L., Besnard, F., Bogner, J., Hilger. H., (2011). "Bio-tarp alternative daily cover prototypes for methane oxidation atop open landfill cells.", Waste Management, 31(5): 1065-1073.

[40] Han, B., Scicchitano, V., Imhoff, P. T., (2011). "Measuring fluid flow properties of waste and assessing alternative conceptual models of pore structure.", 31(3), 344-456.

[41] "Subsurface Investigations-Geotechnical Site Characterization Reference Manual", (May 2002). U.S. Department of Transportation Federal Highway Administration. Publication No. FHWA NHI-01-021.

[42] Hsu, Y., VanCuren, T., Jakober, C., Herner, J., FitzGibbon, M., Blake, D. R., Parrish, D.D., (2010). "Methane emissions inventory verification in southern California, Atmospheric Environment, 44(1):1-7.

[43] Scheutz, C., Samuelsson, J., Fredenslund, A.M., Kjeldsen, P., (2011). "Quantification of multiple methane emission sources at landfills using a double tracer technique." Waste Manage., 31(5):1009–1017.

[44] Galle, B., Samuelsson, J., Svensson, B.H., Börjesson, G., (2001). "Measurements of methane emissions from landfills using a time correlation tracer method based on FTIR absorption spectroscopy." Environmental Science & Technology 35 (1), 21–25.

[45] Czepiel, P., Mosher, B., Harris, R., Shorter, J.H., McManus, J.B., Kolb, C.E., Allwine, E., Lamb, B., (1996). "Landfill CH_4 emissions measured by enclosure and atmospheric tracer methods." Journal of Geophysical Research 101, 16711–16719.

[46] Trégourès, A., Beneito, A., Berne, P., Gonze, M.A., Sabroux, J.C., Pokryszka, Z., Savanne, D., Tauziede, C., Cellier, P., Laville, P., Milward, R., Arnaud, A., Levy, F., Burkhalter, R., (1999). "Comparison of seven methods for measuring methane flux at a municipal solid waste landfill site." Waste Management and Research 17, 453–458.

[47] Babilotte, A. (2011). "Field comparison of methods for assessment of methane fugitive emissions from landfills." Report for Environmental Research & Education Foundation. 127 pp.
http://erefdn.org/publications/uploads/FugitiveEmissions_FinalReport.pdf (accessed April 2015)

[48] Goldsmith, J., C. Douglas, Chanton, J., Abichou, T., Swan, N., Green, R., & Haters, G. (2012). "Methane emissions from 20 landfills across the United States using vertical

radial plume mapping.", Journal of the Air and Waste Management Association, 62(2): 183-197.

[49] Green, R. B., Hater, G. R., Thoma, E. D., Dewees, J., Rella, C. W., Crosson, E. R., Gold-smith, C. D. & Swan, N. (2010). "Methane Emissions Measured at Two California Landfills by OTM- 10 and an Acetylene Tracer Method.", In Global Waste Management Symposium 2010, San Antonio, TX, USA.

[50] Peischl, J., et al. (2013) " Quantifying Sources of Methane Using Light Alkanes in the Los Angles Basin, California.", J. Geophys. Res. Atmos. 118:4974-4990.

[51] Adams, B.L., Besnard, F., Bogner, J., Hilger. H., (2011). "Bio-tarp alternative daily cover prototypes for methane oxidation atop open landfill cells.", Waste Management, 31(5): 1065-1073.