APPENDIX J
DRAFT ZONE A RESTORATION TIME FRAME ASSESSMENT
PASCO LANDFILL NPL SITE

Prepared by

GSI Environmental

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DRAFT Ver. C

Zone A Restoration Time Frame Assessment
Pasco Sanitary Landfill

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report estimates the restoration time frame over which the Zone A Soil Vapor Extraction (SVE) system would have to operate to satisfy compliance requirements at the Pasco Sanitary Landfill. The key question, assumptions, and approach are summarized below.

Key Question

What is the restoration time frame for the Zone A SVE system should it be selected as the remediation technology in the final Cleanup Action Plan? In other words, how many years will the SVE system need to operate before the required cleanup levels at the points of compliance are achieved and the system can be shut down?

What is Restoration Time Frame?

Restoration Time Frame is how many years the SVE system will need to operate before the required draft cleanup levels in groundwater are achieved and the system can be permanently shut down. At Zone A, the point of compliance is the edge of the waste in the zone. Restoration time frame is confirmed with *Rebound Testing* that shows if groundwater cleanup levels will permanently remain below their cleanup levels.

Key Assumptions

- It is assumed that the most likely operational scenario is one where the SVE system (shallow, intermediate, and deep vapor extraction wells) can be selectively operated without any material compromising effect of in-situ temperature or thermal oxidizer limitations starting in mid-2017.
- Volatile organic compounds (VOCs), in particular trichloroethene (TCE), are the controlling constituents used as a proxy in this analysis for meeting draft Clean Up Goals (dCULs) in groundwater leaving the Zone A boundary.
- The source mass, soil vapor, and groundwater concentration are all related in a linear fashion.

Approach

Two approaches were used to determine key input data for the restoration time frame analysis - the time required for the drums to release flowable liquids and the percent contaminant mass that must be removed from the system to reach groundwater cleanup levels:

1. *Drum Failure Model:* A drum failure model based on actual evaluation of the corrosion rate of drums emplaced at Dept. of Energy sites, including the Hanford Site was used to estimate the likely failure rate of the drums in Zone A over time (Section 2).
2. *Percent Reduction Analysis:* Three methods were used to estimate the required percentage reduction in source mass to meet dCULs (Section 3).

Then, two different methods and lines of evidence were used to estimate the restoration time frame, each with different working assumptions and criteria.

- *Method 1 – Vapor Concentration Trend Method:* SVE system vapor concentration vs. time data were fit to a first order decay model to estimate the time required to reach dCULs (Section 4).

- *Method 2 – Box Model:* Data on the volume of waste emplaced in Zone A and a range of future SVE removal rates were used to develop statistically-based restoration time frames. Minimum, Most Likely, and Maximum values were estimated for seven key quantities used as input data for the Box Model (Section 5).

Results

Key results of the analysis are:

- *Drum failure model (Section 2):* All of the drums in Zone A most likely had pitting and corrosion failures by the year 2008 thereby releasing all or most of their liquid contents. In addition, all drums are predicted to experience structural failure by the year 2029, 12 years from now (2017). As a conservative measure, a five-year period was added to all the restoration time frame calculations to consider the possibility that some drums may not yet have released their contents (as of 2017).

- *Three supporting calculations (Section 3):* Between 90% and 99% of the source mass present in 2017 needs to be removed to meet the groundwater dCULs.

- *Method 2 Box Model (Section 5):* About half the total VOC mass has been removed to date.

- The restoration time frames for Method 1 and Method 2 are shown below (Sections 4 and 5).

Restoration Time Frame Method	Mostly Likely Restoration Time Frame	90% Chance Restoration Time Frame is Less Than
Method 1 Trend Method	14 Years	*not applicable*
Method 2 Box Model	16 Years	33 Years

- Restoration time frame Methods 1 and 2 use two very different approaches to estimate time frames. However, both methods provide similar results, increasing the reliability of the prediction.

- Rebound testing should be performed when the SVE system gets closer to its remediation goal as assessed during successive five-year reviews.

1.0 INTRODUCTION

Approximately 35,000 drums of industrial waste were disposed in Zone A between April 1972 and mid-1975 within the larger Pasco Sanitary Landfill (Anchor QEA, 2014). The drums contained a variety of chemicals including paint waste, metal cleaning and finishing waste, wood preserving waste, metal etching, and pesticides. The Zone A cell was placed on reworked native soils, at least some of which appear to have included burned municipal waste (referred to as “Mixed Debris”) from the former burn trench area. The first drums disposed at Zone A were “randomly placed” and subsequently bulldozed to the west side of Zone A. In this manner, approximately 10,000 drums were damaged or destroyed to the point of releasing all free liquids. The other, approximately 25,000 drums were stacked as much as four-high, and represent the potential source of unreleased free liquids. A bulldozed soil berm separated the drums to the west from the stacked drums to the east.

The predominate volatile organic compounds (VOCs) in Zone A soils (based on Soil Vapor Extraction (SVE) data) are mono-aromatics (primarily toluene and xylene) and ketones (primarily methyl isobutyl ketone (MIBK), methyl ethyl ketone (MEK), and acetone. These compounds are readily biodegradable either aerobically or anaerobically (e.g., see Lyman et al., 1990; Howard et al., 1991; Wiedemeier et al., 1999) and have biodegraded in Zone A (see Section 5.3). In addition, lesser volumes of chlorinated volatile organic compounds (CVOCs) such as trichloroethene (TCE) are present, many of which are not aerobically biodegradable. The CVOCs are the main site constituents of concern found in groundwater. A two-mile long CVOC plume originating from Zone A and the Municipal Solid Waste (MSW) Landfill was observed in the mid-1990s (Figure 1.1).

Figure 1.1. *Reduction in volatile organic compound (VOC) concentrations in the off-property groundwater plume 1996-2013. Remediation measures included startup of the SVE system in 1997; installation of an engineered cap in 2002; and startup of an enhanced SVE system in 2012.*

An engineered cap consisting of a high-density polyethylene (HDPE) liner was installed over Zone A in 2002. Soil vapor extraction began in 1997 with up to five SVE wells being operated around the perimeter of Zone A. By March 2012, this system had removed 445,000 pounds of VOCs (Figure 1.2), and the CVOC groundwater plume was confined to the property boundary (Figure 1.1).

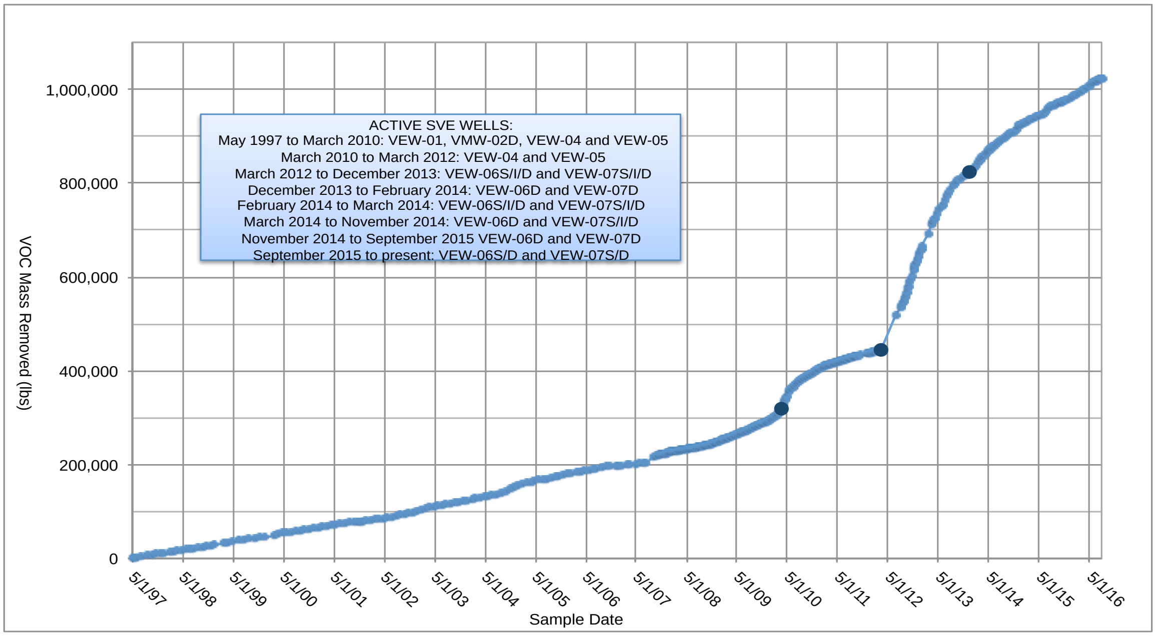


Figure 1.2. *SVE system cumulative VOC removal from May 1997 to July 2016 (pounds). Source: EPI, 2017.*

To better protect groundwater and increase mass removal from Zone A, the original SVE system was enhanced in 2010-2011 with two new well clusters (each with a shallow, intermediate, and deep well configuration) in a north-south alignment near the center soil-berm portion of the Zone A unsaturated zone. Extraction from the previous SVE wells was halted with the operation of the new wells. The enhanced SVE system removed 267,000 pounds of VOCs in its first year of operation. Figures 1.2a and 1.2b, created by SCS Engineers, provide plan view and cross section depictions of the expanded SVE system. On Figure 1.2b, the shallow, intermediate, and deep SVE well screen intervals are labeled S, I, and D, respectively, for the northernmost SVE location, VEW-6. (Because of the close proximity of the S, I, and D SVE wells at each location, the diagram shows all three screened intervals placed on one vertical line. In reality, there are three separate wells at the VEW-6 location and three separate wells at the southernmost location, VEW-7.)

However, subsurface temperatures increased due to operation of the SVE system starting in 2012. A 2013 analysis by GSI Environmental Inc. (GSI, 2013) indicated this was consistent with aerobic biodegradation of organic material in the subsurface. Temperatures as high as 148°F were observed in a downhole temperature monitoring survey and as high as 144°F in the wellhead vapor streams. In addition, elevated carbon monoxide concentrations have been detected at the site (up to 1400 parts per million volume (ppmv). A subsurface combustion event was observed in an adjacent Mixed MSW Waste Disposal Area in December 2013, which may or may not be related to SVE operation (Anchor, 2016). Because of these issues, Ecology became concerned about potential subsurface combustion underlying the Zone A drum area and, in particular, the potential combustion in the mixed debris layer within Zone A. As a result, the SVE system has been operating at a reduced level since December 2013, averaging 76,000 pounds of VOCs removed per year, with the objective being to control the release of contaminants to groundwater and deferring the second SVE objective of mass removal until operational issues and risks are addressed.

Through July 2016, the SVE system at Zone A has removed 1,022,000 pounds of VOCs since 1997, with 577,000 pounds of this having been removed by the enhanced SVE system since March 2013 (EPI, 2017). Installation of a regenerative thermal oxidizer (RTO) was initiated in 2016 to allow for more reliable and potentially higher removal rates following resolution of the subsurface combustion issue.

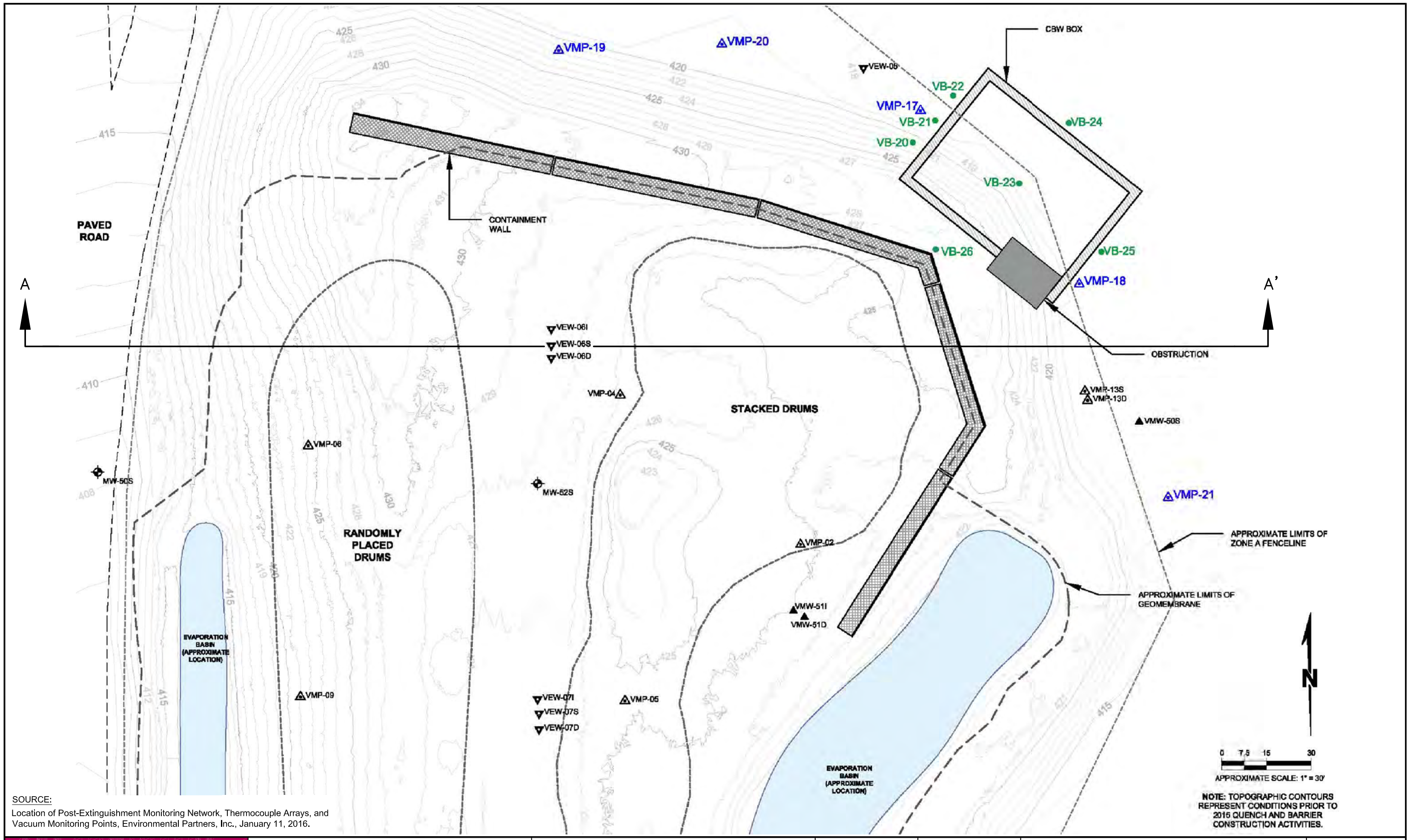
The objective of this report is to further support the selection of the site remedy by determining the restoration time frame, i.e., the time required to remove enough contaminant mass from Zone A so that the SVE can be permanently shut off (following typical SVE rebound testing) and still achieve compliance with groundwater draft (and final) Clean Up Goals (dCULs).

The restoration time frame analysis was performed assuming:

- The most likely scenario is that SVE system (shallow, intermediate, and deep vapor extraction wells) can be operated at a higher rate starting in mid-2017 with a most likely value of 267,000 pounds removed per year (and a potential range between 59,300 and 533,000 pounds per year (see Table 5.4)). In reality, the approximate SVE removal rate is controlled by constraints such as:
    - If no intermediate wells are in operation due to temperature concerns: 90,000 lbs/yr.
    - If intermediate wells are in operation but emissions are limited by Title V air permit: 330,000 lbs/yr.
    - No constraints on operating wells or from Title V permit: 730,000 lbs/yr.
- VOCs, in particular TCE, are the controlling constituents used as a proxy in this analysis for meeting dCULs in groundwater leaving the Zone A boundary.
- The Zone A drums are naturally corroding and releasing their flowable liquids content at a predictable rate. The most likely scenario is that all Zone A drums will have corroded and at the latest will have released all of their contents by the year 2023.

Key Points

- Soil vapor extraction has removed over a million pounds of VOCs from Zone A since 1997.
- The SVE system is being operated at a reduced level since late 2013 primarily because of concerns about underground combustion adjacent to Zone A, the potential combustion in the mixed debris layer within Zone A, and temporary thermal oxidizer constraints. This analysis assumed these issues can be resolved and that the SVE system can be operated without these constraints materially diminishing SVE effectiveness and objectives in the future.
- The goal of this report is to estimate the restoration time frame, i.e., the time required to remove enough contaminant mass from Zone A so that the SVE can be permanently shut off, following typical SVE rebound testing, and still meet and sustain dCULs or final CULs in groundwater.



NOTE: TOPOGRAPHIC CONTOURS REPRESENT CONDITIONS PRIOR TO 2016 QUENCH AND BARRIER CONSTRUCTION ACTIVITIES.

SOURCE:
Location of Post-Extinguishment Monitoring Network, Thermocouple Arrays, and Vacuum Monitoring Points, Environmental Partners, Inc., January 11, 2016.

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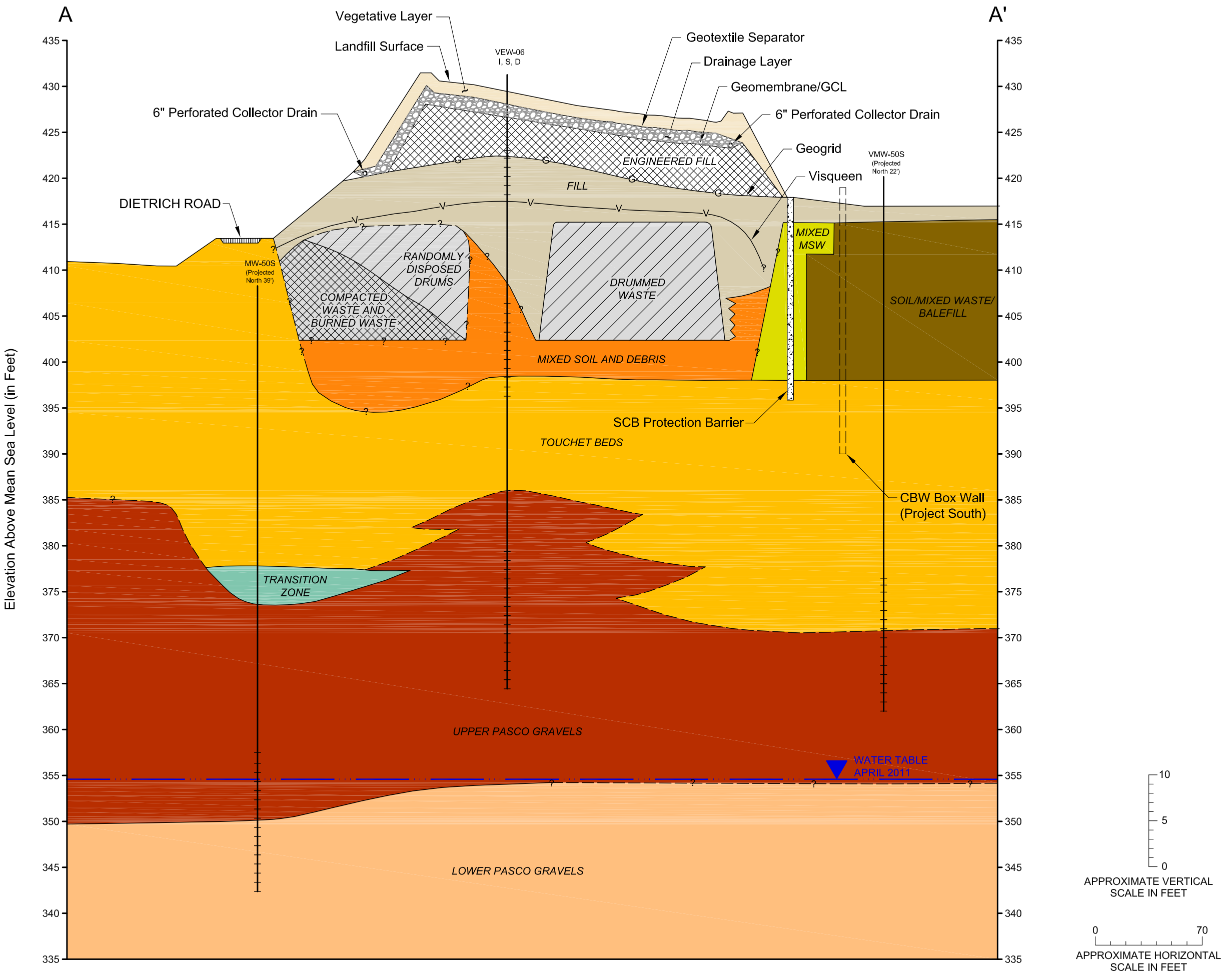
PROJECT NO.	04209046.04	DES BY	EMS
SCALE	AS SHOWN	CHK BY	JMR
CAD FILE	FIGURE 1	APP BY	JJW

ZONE A SITE PLAN

TECHNICAL REVIEW OF PASCO LANDFILL
ZONE A SOIL VAPOR EXTRACTION SYSTEM

DATE AUGUST 2016

Fig 1.2a



SOURCE:

Location of Post-Extinguishment Monitoring Network, Thermocouple Arrays, and Vacuum Monitoring Points, Environmental Partners, Inc., January 11, 2016.

Figure 5.4.1-2, Draft Focused Feasibility Study, Pasco Landfill National Priorities List Site, Anchor QEA, LLC, September 2014.

Zone A Cover Replacement Details Sheet 1, Drawing No. D7, AECOM, August 6, 2015.

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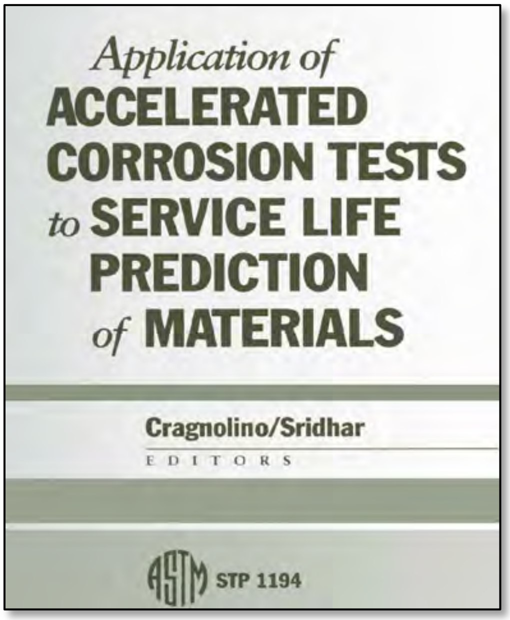
PROJECT NO. 04209046.04	DES BY EMS	ZONE A CROSS SECTION	DATE AUGUST 2016
SCALE AS SHOWN	CHK BY JMR	TECHNICAL REVIEW OF PASCO LANDFILL ZONE A SOIL VAPOR EXTRACTION SYSTEM	FIGURE Fig 1.2b
CAD FILE FIGURE 2	APP BY JJW		

2.0 RELEASE OF FLOWABLE LIQUIDS FROM DRUMS

The restoration time frame in Zone A is partly controlled by the status of the stacked drums that were emplaced in 1973-1975. If a large fraction of the drums are still intact, the restoration time frame may be delayed until the drums corrode and release their flowable liquid content and become subject to the timeframe analysis in Sections 3, 4, and 5.



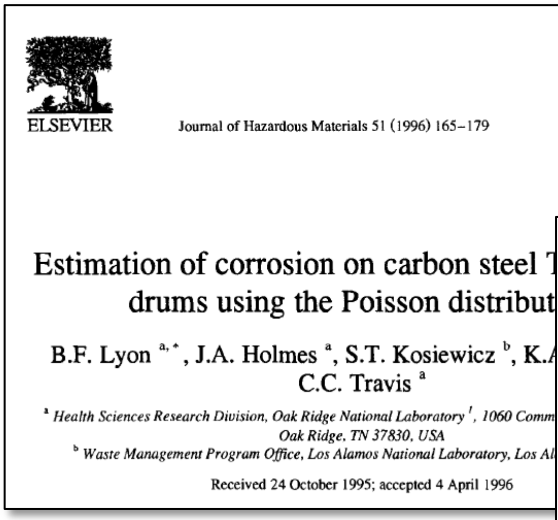
Application of
ACCELERATED
CORROSION TESTS
to SERVICE LIFE
PREDICTION
of MATERIALS

Cragnolino/Sridhar
EDITORS

ASTM STP 1194

To evaluate the status of the drums, three drum corrosion studies were evaluated and applied to the stacked drums in Zone A:

- A drum failure study performed at the Idaho National Engineering Laboratory (Zerker and Beitel, 1995).
- A drum failure model developed by Hanford Site reseachers in 1994 (Duncan et al., 1994).
- The Hanford model expanded by Los Alamos National Laboratory researchers (Duncan et al., 1994; Lyon et al., 1996; see covers below).



ELSEVIER Journal of Hazardous Materials 51 (1996) 165–179

JOURNAL OF HAZARDOUS MATERIALS

Estimation of corrosion on carbon steel T
drums using the Poisson distribut

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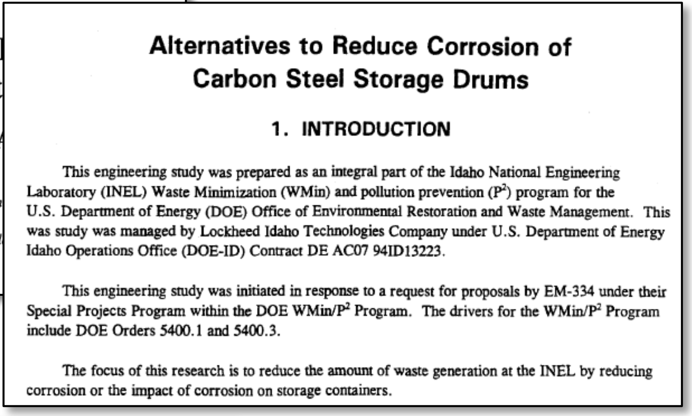


Alternatives to Reduce Corrosion of
Carbon Steel Storage Drums

1. INTRODUCTION

This engineering study was prepared as an integral part of the Idaho National Engineering Laboratory (INEL) Waste Minimization (WMin) and pollution prevention (P^2) program for the U.S. Department of Energy (DOE) Office of Environmental Restoration and Waste Management. This was study was managed by Lockheed Idaho Technologies Company under U.S. Department of Energy Idaho Operations Office (DOE-ID) Contract DE AC07 94ID13223.

This engineering study was initiated in response to a request for proposals by EM-334 under their Special Projects Program within the DOE WMin/P^2 Program. The drivers for the WMin/P^2 Program include DOE Orders 5400.1 and 5400.3.

The focus of this research is to reduce the amount of waste generation at the INEL by reducing corrosion or the impact of corrosion on storage containers.

PINHOLE CORROSION OF CH-TRU WASTE CONTAINERS
BY VOLATILE ORGANIC COMPOUNDS

D. P. Zeek
Lockheed Martin Idaho Technologies Company
Idaho National Engineering and Environmental Laboratory

2.1 Idaho National Laboratory Studies

A detailed study of *"an epidemic of corroded contact-handled transuranic waste drums (CH-TRU)"* was performed by the Idaho National Laboratory in 1998 (Zeck, 1998). This waste was placed into drums between 1980 and 1983 and stored in buildings with no soil contact. By 1996 (~14 years), over 300 drums had pinhole leaks that were about 2 mm in diameter (Figure 2.1). The authors concluded this internal corrosion was caused by chlorinated VOCs in the drums:

- *The pinholes are localized pitting corrosion caused by HCl (hydrochloric) acid, which occurs predominately in the headspace of the drums.*
- *HCl acid formation is directly related to the chlorinated hydrocarbon VOCs in the waste and the steel of the unlined drum*.

In a second document from Idaho National Engineering Laboratory, Zirker and Beitel (1995) identified a pin hole corrosion problem and associated "deleterious waste streams" to 55-gal steel drums and estimated the "time to failure" for several wastes (Table 2.1).

Table 2.1. *Deleterious waste streams to 55-gal steel drums stored in buildings (Zirker and Beitel, 1995).*

Description of the Waste	Time In Storage (Years)	Time to Failure (years)	Time to Failure (years)
Oil/solvents	7	4	11
Oil and grease	5	4	9
Halogenated and nonhalogenated contaminated water (solvents approximately 100 ppm)	5-10	2	7-12
Bulked TCA still bottoms	2	1	3
Paint stripping operations	13	2	15

Note these drums were not emplaced in the ground, but stored in buildings that protected the drums from the weather but not moderate temperatures. (The presence of plywood spacers between vertically stacked drums may have also increased corrosion due to potentially corrosive fire-retardant chemicals or due to adsorption of condensing water, but these effects are uncertain.) Drums from "paint stripping operations" had an estimated lifetime (time in storage + time to failure) of only 15 years, while the chlorinated solvent containing drums had much shorter lifetimes (only 4 years for TCA still bottoms).

Together, these studies show that even drums that are not in direct contact with soil can corrode relatively rapidly (within 15 yrs). The presence of chlorinated solvents in the drums is associated with significant rapid corrosion and pinhole leaks in steel drums.

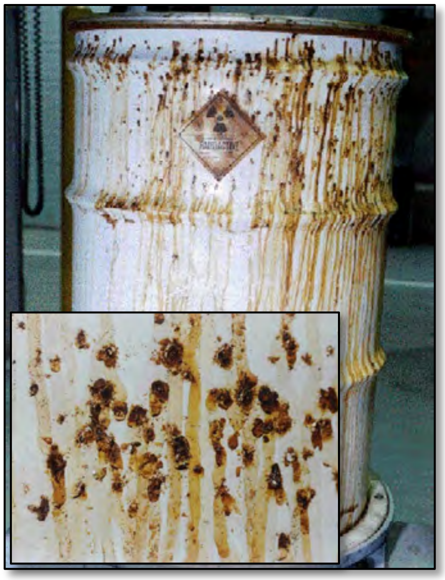


Figure 2.1. *Pinhole corrosion of drums containing chlorinated solvents in CH-TRU waste at Idaho National Lab (Zeck, 1998). Inset is close up photo of pinhole corrosion.*

(Note that the pinhole leaks near the top of the drum cause liquid to migrate down on the outside of the drum likely increasing the *external* corrosion rate for these drums.)

2.2 Hanford Corrosion Failure Model – External Corrosion

Duncan et al. (1994) developed a statistical model to *"project the probability of corrosion failure in retrievably stored drums at the Hanford Site. The model applies the Poisson probability distribution to data on storage container type and age, and uses estimated corrosion rates for the various storage configurations and failure modes to calculate the projected number of failures that can be expected."*

The corrosion failure model was based on a wide variety of datasets, including:

- *"At the Idaho National Engineering Laboratory (INEL) in Idaho Falls, Idaho, 65% of the drums stored for 18 to 21 years were breached, with several containers having lost structural integrity. This corresponds to a median corrosion rate in the breached containers of approximately 0.102 mm/year." (This is equal to 4 mils/yr, where a mil is 1000th of an inch).*
- *"Jaske reported that soils from the NIST study similar to Hanford Site soils had rates of maximum general corrosion penetration from approximately 0.076 mm/year (3 mil/year) to 0.229 mm/year (9 mil/year)."*
- *"There have been several assessments and examinations of corrosion of buried steel at the Hanford Site, in the two environments of direct soil burial and under plastic tarp covering. The oldest and perhaps the most comprehensive survey of direct soil effects was performed by Jaske, for a variety of buried piping materials. The observed corrosion rates averaged 0.127 mm/year (5 mil/year) for general corrosion and 0.229 mm/year (9 mil/year) for pitting corrosion."*
- *"At the Hanford Site there have been several investigations of corrosion under the tarp coverings. In 1982, an inspection was carried out on drums stored over 8 years using visual and ultrasonic techniques."*

The corrosion model provides drum lifetime estimates for four different groups of drum storage techniques (Table 2.2 and Figure 2.2) used at Hanford.

Table 2.2. *Four types of Hanford drums/emplacement groups modeled by Duncan et al., 1994). Note 1 mil is 1000th of an inch.*

Group	Emplacement time span	Drum wall thickness	Corrosion rate mm/yr (mil/yr)		Comment
			Pitting/ crevice	General	
1	1970-1972	1.27 mm (50 mil)	0.229 (9)	0.127 (5)	Painted 17-H drum, direct soil contact
2	1973-1975	1.27 mm (50 mil)	0.051 (2)	0.025 (1)	Painted 17-H drum, stacked under tarp
3	1976-1980	1.52 mm (60 mil)	0.051 (2)	0.025 (1)	Painted 17-C drum, stacked under tarp
4	1981-1988	1.52 mm (60 mil)	0.025 (1)	0.013 (0.5)	Galvanized 17-C drum, stacked under tarp

For **Hanford drums**, Jackson et al. (1983) report the drum type history as: "*Initially, the lighter gauge 55 gallon steel drums, designated DOT 17-E and 17-H, were used, some of which were reconditioned. In later years the DOE [(Department of Energy)] Sites have virtually all changed to the heavier 16 gauge DOT 17-C drums."* This is supported by the data in Table 2.2 which shows thicker-walled drums being used after 1975 and galvanized drums after 1980.

Zone A drums were emplaced from April 1972 to mid-1975 (1975 was used for calculation purposes). The USEPA (1976) reported that as of 1976 it was common practice to use "old drums" for transporting still bottom waste (designated paint waste in Zone A Drum Inventories) due to cost reduction pressure:

> *Compliance with Department of Transportation (DOT) regulations (CFR 8173.28) requires the use of new or reconditioned drums which have undergone pressure tests for the hauling or disposal of spent or reclaimed solvents which have a flash point below 38°C (100°F). It appears that in many areas these DOT regulations are not enforced and that old drums are being used to ship solvents to and from reclaimers. Strict enforcement of these regulations could add up to 13¢/liter (50¢/gal.) to the total cost of hauling solvents in drums to and from reclaimers.*

The same document (USEPA, 1976) surveyed 46 plants in the paint and contract solvent reclaiming industry. Only two of these plants indicated using special handling for disposal of potentially hazardous wastes.

Figure 2.2 shows a photo of the stacked drum emplacement in Zone A. Table 2.3 describes the similarities and differences between the Hanford Drum model and Zone A.

Table 2.3. *Comparison of Hanford vs. Zone A drum material and drum emplacement. Due to the use of thinner vs. thicker drums at Hanford, Zone A drums likely exhibit behavior between Group 1 and Group 2, and less likely to exhibit Group 3 behavior.*

	Hanford Drums	Zone A
When Emplaced	Group 1: 1970-1972. Group 2: 1973-1975 Group 3: 1976-1980.	April 1972 to mid-1975.
Drum Material	Groups 1, 2, and 3: Steel. Group 4: Galvanized (this was described as an "alternative material" at Hanford and does not appear to be commonly used for commercial purposes).	Almost certainly conventional steel drums for solvents in Zone A. Very unlikely galvanized drums used.
Drum Wall Thickness	Two drum types: Groups 1, 2: Thinner walls 17-H (50 mil). Group 3 and 4: Thicker walls 17-C (60 mil).	Thinner 17-H drums may likely be more prevalent based on lower cost and the timing of use of thinner vs. thicker drums at Hanford.
Direct Soil Contact?	Yes for Group 1 No for Groups 2, 3, and 4.	Yes for drums on top and outside of drum stack. Potentially no for some interior drums (?).
Other Factors	Groups 2, 3, 4 separated by plywood that may increase corrosion due to a corrosive fire-retardant chemicals in the plywood, and entire stack covered by tarp to prevent soil contact.	No spacers or tarp but stacked directly on top of each other and covered with soil (Figure 2.2). Common debris, empty pesticide containers, and other unidentified waste was backfilled between the Zone A drums.
Materials in Drums	"These wastes consist of dry waste (e.g., soiled clothing; laboratory supplies; and tools packed in cardboard, wood, or metal containers) and industrial waste (primarily items of failed process equipment packaged in plastic shrouds" and boxes of various materials. (Duncan et al., 1994)	VOC containing waste would be liquid not dry. Over 90% of the drums were designated as "Paint" waste (24,200 drums) and metal casting waste (8774 drums) (see Table 5.1, Inventory B). Based on Idaho drum study, drums containing chlorinated solvents like TCE would likely have higher corrosion rates.

***Figure 2.2**. Close up photo of Zone A Stacked Drum emplacement. The Franklin County Planning Commission (1987a) wrote: "The space between the drums was backfilled with common debris, empty pesticide drums and small unidentified amounts of waste."*

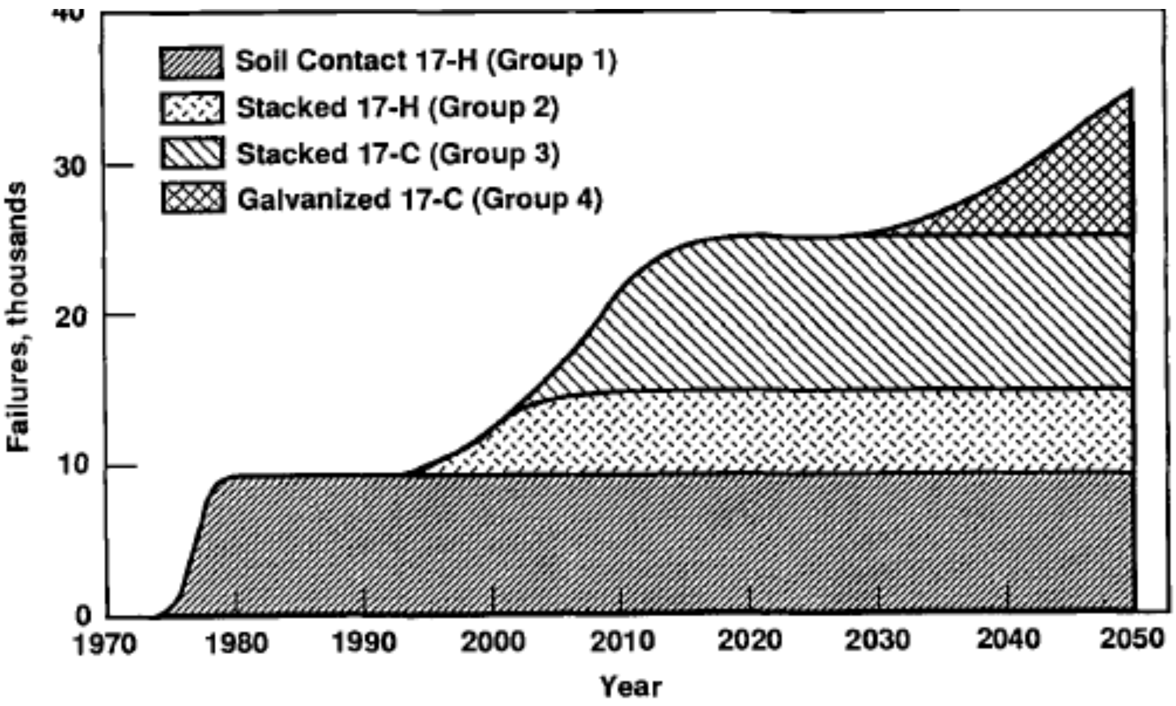
Overall, the Hanford drum model indicates the general corrosion behavior of the Zone A drums:

- Zone A drums that come in direct contact with soil are likely to behave closer to Hanford Drum Group 1.
- Zone A drums in the interior the drum stack may exhibit behavior closer to Group 2 until structural collapse of the outer drums occurs and the interior drums come in contact with soil.
- Although less likely, if there are thicker walled drums in the interior of the Zone A drum stack they would behave similar to Group 3 until they come in direct contact with soil.

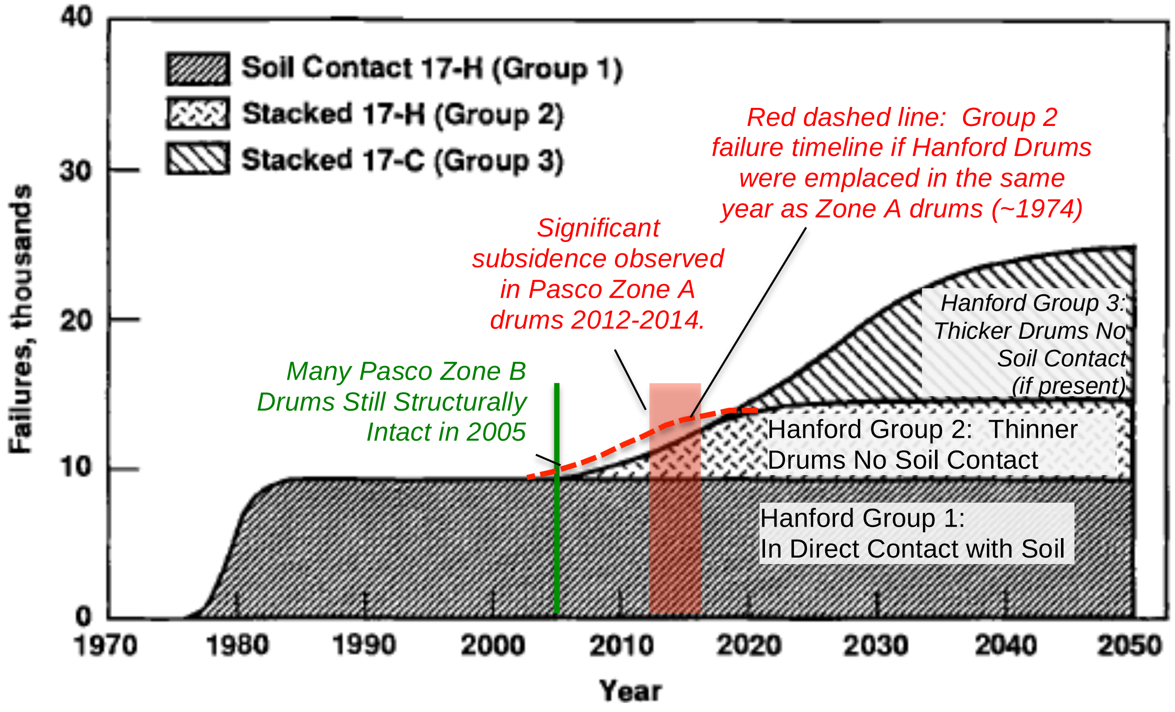
The Hanford Drum model was used to predict two failure modes: pitting corrosion (a breach or hole in the drum allowing leakage of liquid materials) and general corrosion (actual loss of structural integrity that results in drum collapse). Figure 2.3 shows the predicted failures for Hanford drum Groups 1, 2, and 3. Applying the Hanford drum model data in Figure 2.3 to Zone A indicates:

- Drums in Group 1, Group 2, and Group 3 were predicted to start having *pitting failures* within 3 years after being emplaced, and all drums would have experienced *pitting failures* within 41 years. For Zone A drums (emplaced around 1974), each drum would experience their initial pitting failures between 1977 and 2015.
- Group 1 drums (direct soil contact) were all predicted to have *structural failure* within 5 to 13 years of being emplaced (Figure 2.3). For Zone A drums in contact with soil, this would have occurred in the 1979 to 1988 time frame.

- Group 2 drums (under tarp, no contact) were all predicted to have *structural failure* within 31 to 48 years of being emplaced (Figure 2.3). For Zone A drums in contact with soil, this would have occurred in the 2005 to 2022 time frame.



Projected drum failures (pitting corrosion).



Projected drum failures (loss of structural integrity).

Figure 2.3. *Predicted drum failure timeline for Hanford Site drums. Zone A drums are most similar to the drums in Group 1 and Group 2. It is less likely that thicker Group 3 drums are present in Zone A. The observed behavior at Zone A and Zone B may be correlated to Hanford Group 2 type drums.*

Two events provide support for the Hanford drum model results. First, a photo of the Zone B drum excavation (Figure 2.4) indicates that a few drums that were in contact with soil may have collapsed but most of the drums in the interior of the drum stack appear to be intact. This is consistent with the Hanford Group 2 behavior. Note there are differences in the Zone A and Zone B drums that would likely cause more corrosion in Zone A vs. Zone B:

- Zone A drums were likely in better condition. Figure 2.4 and the USEPA Solvent Reclamation report (1976) suggest that high quality drums were likely not used. Additionally, the Franklin County EIS (1987b) discusses the potential condition of the Zone B drums as: *“Unsubstantiated reports claim that unsealed and leaking drums were received for disposal by RRC from Rhodia. However, Mr. Larry Dietrich has stated that Rhodia drums were all new and in excellent condition."*
- Some of the Zone A drums contained chlorinated solvents which are known to accelerate pinhole corrosion.

Figure 2.4. *Zone B drum excavation. Some drums near the surface in contact with soil appear to have collapsed, while most of the drums in the interior of the drum stack still appear structurally intact (although they may have pitting failures that cannot be seen in the photo).*

Second, higher rates of subsidence in Zone A were observed in the 2012 to 2014 time frame (Figure 2.5). This is consistent with the Hanford Group 2 behavior when the drum model shown in the bottom panel of Figure 2.3 is adjusted for a 1974 emplacement date (red dashed line): the Zone A drums were emplaced in 1974 while the Hanford Group 2 drum model had emplacement in 1978. Note the start up of the SVE system in 2012 and subsequent heating of the Zone A soil may have contributed to drum failure and subsequent subsidence. Operation of the enhanced SVE in 2012 would likely not be enough to cause significant subsidence alone however.

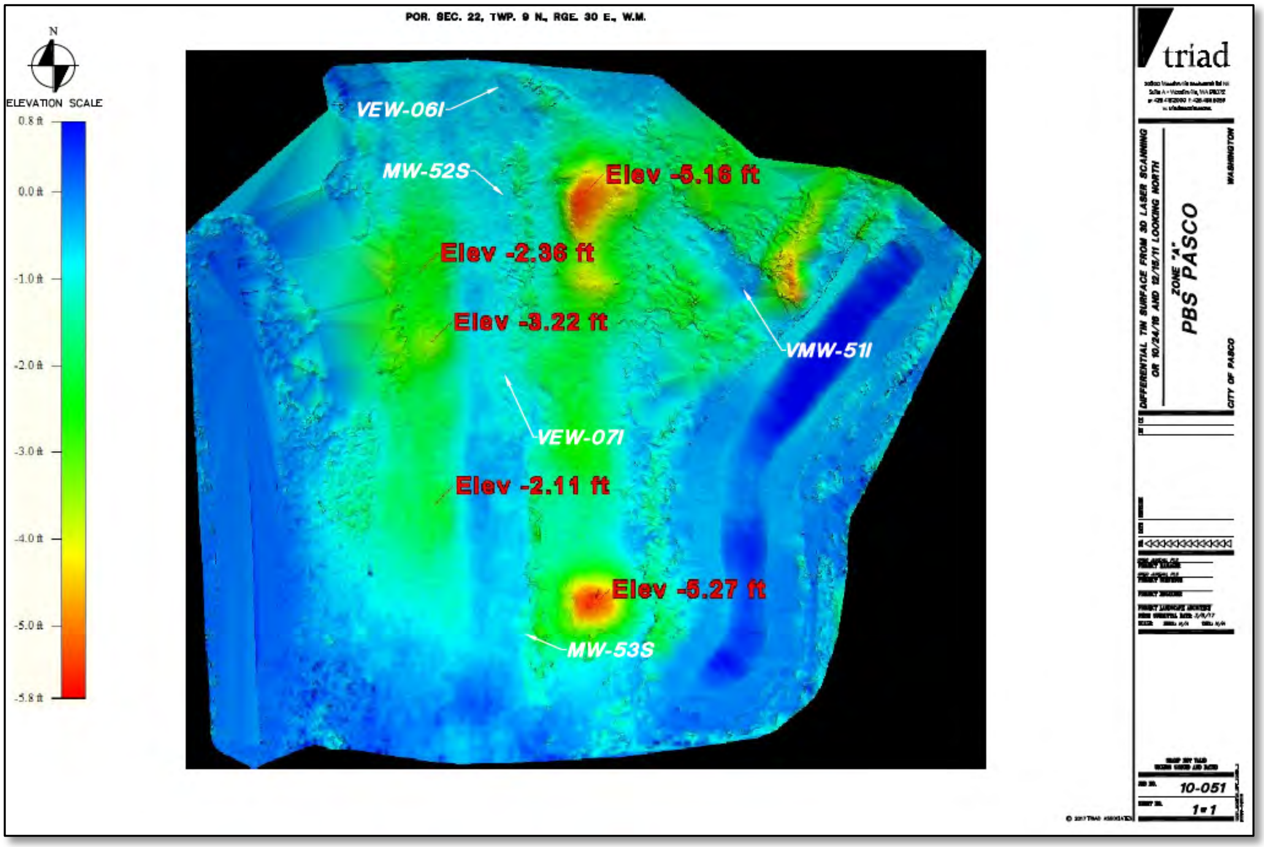


Figure 2.5. *Change in elevation in Zone A from Dec. 2011 to October 2016 due to subsidence. The timing of this subsidence correlates to the collapse of Hanford Group 2 drums.*

Overall, the Hanford drum model supports the conclusion that all of the Zone A drums have experienced pitting failures that would cause the leakage of liquid contents in the drums to the surrounding soil. It also supports the conclusion that most of the Zone A drums have experienced structural failure and have collapsed.

2.3 Los Alamos Drum Failure Model – External Corrosion

Lyon et al. (1996) expanded the Hanford drum model and applied a Monte Carlo statistical approach to estimate the timing of drum failure at Dept. of Energy sites. They stated: *"[t]he purpose of this paper is to describe one approach to estimating the corrosion of TRU waste* *containers in an environment typical of that used within (DOE) sites."* Their model focused on storage methods where the drums were not in direct contact with soil, therefore, application of this model to Zone A drums likely underpredicts the corrosion rate and overpredicts the amount of intact drums at any time.

The model assumes a range of potential corrosion rates and drum wall thicknesses (both thinner and thicker walled drums):

- Low, Medium, and High estimates of the corrosion rate of 0.5, 1, and 2 mil/yr for general corrosion and 1, 2, and 4 mil/yr for pitting corrosion. Note that Lyon et al. (1993) use a low end corrosion rate of 0.5 mil/yr for general corrosion and 1 mil/yr for pitting corrosion because some of the drums at DOE facilities were specialized galvanized drums.
- A uniform distribution between 50 and 60 mil for the drum wall thickness (this included the possibility of both thin and thick walled drums).

Some of the key conclusions from their study and implications for the Zone A drums at the Pasco landfill are shown in Table 2.4.

***Table 2.4**. Key conclusions from Los Alamos drum failure model and implications for integrity of Zone A drums.*

Key Conclusions from Los Alamos Drum Failure Model	Implications for Zone A Drums
"Because galvanized steel corrodes at a slower rate than painted steel, this serves as a lower bound in this study. An assumption is made herein that a triangular distribution is used for the average general corrosion rates with a range of 0.5-2 mil per year and a most likely value of 1 mil per year."	Since galvanized drums were almost certainly not used for solvent containing waste in Zone A, it is appropriate to increase the low-end corrosion rates used by Lyon et al. in the triangular distribution.
"The corrosion process is often conceptualized in terms of the degree of localization of the corrosion, with rapidly growing, localized pinholes described by pitting models and with slower growing, more extensive areas depicted in terms of general corrosion models. Although interior corrosion may be significant, its quantification is extremely uncertain." "It is established that pitting (i.e., localized) corrosion occurs faster than general corrosion."	Pitting failures occur much faster than structural collapse. If subsidence observed at the surface of Zone A in the 2012-2014 is due to drum collapse, then there is a high degree of certainty that all of the drums in Zone A have had pitting failures by now.
"External corrosion of the drums on (Idaho National Lab) Pads 1, 2, and 4 is caused by a combination of environmental conditions and localized weaknesses of the drum structure. The drum on the pads have been in an environment of darkness, high humidity, and relatively little temperature variation for a span of several years."	Zone A drums that are not in contact with soil have been exposed to the same environment as the Idaho National Lab drums: darkness, high humidity, and little temperature variation (but without plywood spacers).
"This simple analysis predicts that once the drums begin to fail, it will require only a short time until nearly all fail."	If the subsidence in 2012-2014 is indicative of drum collapse, then all of the conventional steel drums at Zone A will have collapsed within a few years.

The Los Alamos drum failure model was applied to Zone A with all the same input data except low end corrosion rates: for general corrosion the rate was increased from 0.5 mil/yr to 0.75 mil/yr; and for pitting corrosion the low end rate was increased from 1 mil/yr to 1.5 mil/yr. As a conservative measure, both thick and thin drums were assumed to be emplaced in Zone A.

Table 2.5 shows the quantitative results from the Lyon drum failure model as the percent of drums that would have failed via pitting failures and via general corrosion (structural failures).

Table 2.5. *Los Alamos drum model results. The model assumes no direct contact with soil and no internal corrosion, likely making it conservative (underpredicts corrosion) when applied to Zone A. Percent of drums with either pitting or general corrosion failures assume emplacement in the 1974 time frame. General corrosion failure indicates structural integrity failure (drum collapse). Rounded to 1%.*

Year	**Median Percent of Zone A Drums With General Corrosion Failures (%)**	**Median Percent of Zone A Drums With Pitting Corrosion Failures (%)**	**Key Events**
1974	0	0	*Drums emplaced*
1979	0	0	
1984	0	0	
1987	0	<<1%	*First pitting failures*
1989	0	<1%	
1994	<<1%	16	*First structural failures*
1999	<1%	74	
2004	7	98	
2009	31	100	*100% pitting failure*
2012	53	100	*Highest Zone A Subsidence Rates Observed*
2013	60	100	
2014	66	100	
2017	82	100	*Now*
2019	89	100	
2021	94	100	
2022	96	100	
2024	98	100	
2026	99	100	
2029	100	100	*100% structural failure*

35 years for 0% to 100% failure

22 years for 0% to 100% failure

Overall, the Los Alamo Drum Model:

- Indicates that all of Zone A drums have experienced pitting failures by the year 2009, and 82% have experienced structural failure by the present day (year 2017).

- Predicts a significant fraction of the Zone A drums (66%) would have had structural failure at the end of the observed Zone A high subsidence period.

Although it is likely that pitting failures would have emptied most of the drums by now, as an additional safety factor in the calculation it was assumed that the SVE system may have to run five years beyond the calculated restoration time frame shown in Sections 3 and 4. This extends the remediation time frame to beyond 2029, the date when 100% of the drums are predicted to have a structural failure.

Key Points

- Two types of corrosion are considered in drum failure studies: pinhole corrosion where small holes are formed by corrosion, and general corrosion where the drum walls are sufficiently thinned that the drum will collapse due to the lack of structural integrity. Both types of failures are likely to drain most or all of the flowable liquids out of corroded, failed drums.
- Two Idaho National Lab studies showed that certain waste streams, including paint waste, solvents, and halogenated solvents were “deleterious waste streams” that caused internal corrosion that limited the drum lifetime to less than 15 years when drums were stored above ground.
- A statistical drum failure model developed for external corrosion of drums at the Hanford site indicated that Zone A drums would all have pitting failures by the year 2015. Zone A drums in contact with soil would have all failed by 1998, and drums that are not in contact in soil will all have failed by the year 2022.
- Researchers at Los Alamos expanded the external corrosion Hanford model to make it more general and account for uncertainty in the input data. For the most likely case it showed all the drums would have had pitting failures by 2009, and 82% of the drums would have experienced structural failure by now (year 2017).
- Both the Hanford and Los Alamos models predict significant structural failures at Zone A would have started in the 2012-2014 time frame. This is when significant subsidence was observed at Zone A, thereby supporting the accuracy of the models.
- Although pitting failures have likely emptied most of the solvent containing drums at this time due to a combination of internal and external corrosion, as a conservative safety factor it was assumed that the SVE system will have to run for an additional five years beyond the calculated restoration time frames in Sections 4 and 5. This extends the time frame past the year 2029, the year when 100% of the drums are predicted to all have structural failure.

3. 0 HOW MUCH MASS NEEDS TO BE REMOVED?

To perform restoration time frame calculations, the amount of mass removal that is required to reach the dCULs in groundwater needs to be determined. In this section three different methods were used to estimate the percentage reduction in TCE mass required to reach dCULs. Each method is summarized below with results detailed in the referenced Appendices. Methods 1 and 2 apply the same approach to 1995 and 2011 data, respectively. Method 3 applies a more sophisticated modeling approach.

Appendix A provides more detailed discussion regarding SVE and restoration time frame in the following sections:

- A.1 When is it Appropriate to Shut Down (Discontinue Operation) an SVE System?
- A.2 SVE System Performance
- A.3 Restoration Time Frame Methods

Key Assumptions

The three methods used different assumptions. Methods 1 and 2 below assumed that as the mass of a compound in the source zone is reduced, the mass delivered to the groundwater and the resulting groundwater concentration is reduced by the same amount (see Section B.1). This assumption is used in several groundwater models (see the “Declining Rate Method” section in Appendix A.3). Method 3 used a more detailed modeling approach that accounted for the actual transport processes; see Section 3.3 for the assumptions inherent in this method.

3.1 Method 1: TCE Concentration in 1995 vs dCUL

Pre-remediation groundwater concentrations at Zone A were evaluated to provide a line of evidence regarding the approximate overall mass removal required to reach dCULs. This simple method is based on the concepts shown in Appendix B.1.

The average 1995 concentration for TCE in groundwater from two monitoring wells downgradient and closest to Zone A (EE-2 and EE-3) was estimated to be 85 ug/L (see Appendix B.1). Assuming that the source mass and groundwater concentrations are proportional (see Appendix B.1), a 97% reduction in the 1995 TCE source mass would be required to meet the 2.5 ug/L dCUL, that is, 3% of the 1995 TCE source mass can remain and still meet the dCUL.

However, since 1995, the SVE system may have removed approximately 50% of the entire VOC mass originally present in 1995 (see Section 5). Consequently, factoring in the progress of the SVE system, about 6% of the 2016 TCE source mass (equal to ~3% of the 1995 TCE source mass) can be allowed to remain and still reach dCULs.

Therefore, Method 1 indicates that a **94% reduction** in the 2016 TCE source mass is needed to reach dCULs. (This value is used later in Section 3.4 to help develop a range of removals for all the VOC mass in Zone A.)

3.2 Method 2: TCE Concentration in 2011 vs. dCUL

A similar approach was performed using data from 2011. Based on SVE records, the original SVE system was operated at a reduced rate from May 2011 to February 2012 (see Figure 1.2). Because of the lower operational rate, and because the original SVE system only had wells around the perimeter of the source zone and not in the middle of Zone A, it may have had only a minor impact on the transport of TCE vapors to groundwater. Therefore, the mass reduction required to reach dCULs was obtained by comparing the average TCE concentrations in the Zone A source zone wells MW-52S and MW-53S to the dCUL for TCE (Appendix B.2). TCE concentrations during the operation of the enhanced SVE system were not used for this analysis because the enhanced SVE system likely has a significant effect on TCE concentrations in groundwater (Appendix D).

Method 2 indicates that a **66% reduction** in the 2016 TCE source mass is needed to reach dCULs. (This value is used later in Section 3.4 to help develop a range of removals for all the VOC mass in Zone A.)

3.3 Method 3: SVEET Model to Determine Percent Mass Reduction

Truex et al. developed the SVEET (SVE Endstate Tool) model based on their experience managing a large SVE system at the Hanford Site (Truex et al., 2013). This tool matches a non-Hanford site to a library of detailed numerical modeling runs from the STOMP model (PNNL, 2017) to simulate recharge-controlled or gas-phase controlled transport of VOCs from the unsaturated zone to groundwater. They describe the underlying modeling approach as:

> *When vapor-phase transport is an important component of the overall contaminant fate and transport from a vadose zone source, the contaminant concentration expected in groundwater is controlled by a limited set of parameters, including specific site dimensions, vadose zone properties, and source characteristics. Under these circumstances, it is possible to pre-model contaminant transport for a matrix of parameter value combinations that cover a range of conditions and to estimate the results at a specific site by comparing the site-specific characteristics to the characteristics of the pre-modeled scenarios.*

As seen in Figure 3.1 below, the conceptual framework centers on a source area that is present at a specified vertical location within the vadose zone. Additionally, a compliance well is located downgradient from the source. Using site-specific parameters, SVEET predicts the contaminant groundwater concentration at the compliance well, given the source strength (soil gas concentration) and additional vadose zone parameters.

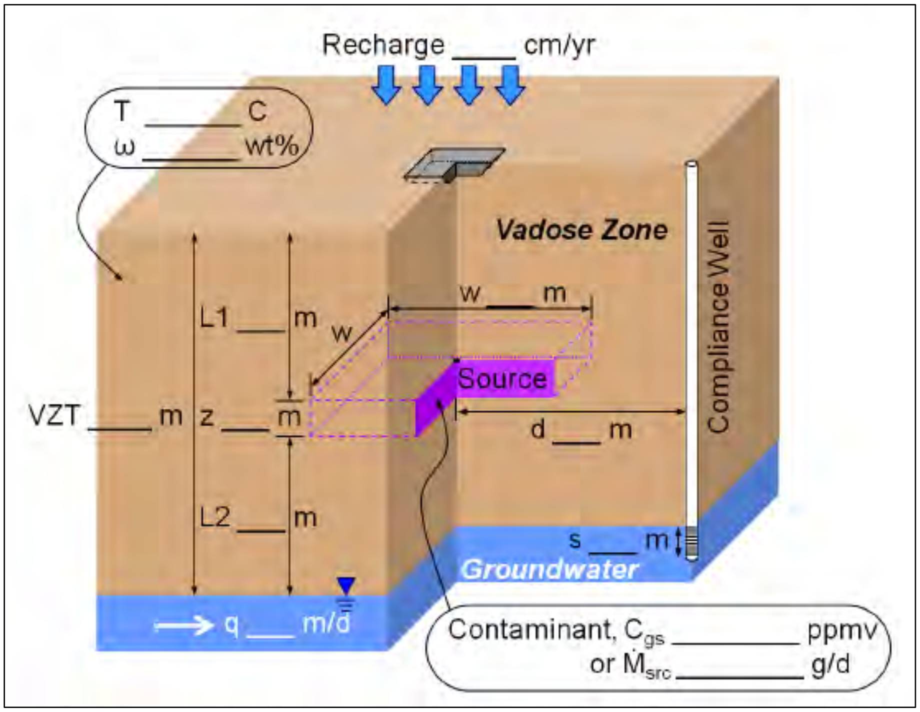


Figure 3.1. *Conceptual model and key model input for SVEET.*

The author of the SVEET tool, Dr. Mike Truex of the Pacific Northwest National Lab (PNNL), was consulted to review the application of SVEET to the Zone A SVE system.

The resulting application suggested that a 97% reduction in the 2017 TCE source mass is needed to reach dCULs.

Table 3.1. Results of Method 3 SVEET analysis for TCE.

Variable	Result
2016 TCE Soil Gas Concentration in Intermediate Zone	959 ppmv 5153 ug/L
Soil Gas Concentration Required to Reach dCUL of 2.5 ug/L	30 ppmv 162 ug/L
Required % Reduction in Soil Gas	***97%***

Details on the SVEET model and limitations to the results are presented in Appendix B.3.

3.4 Results

The estimated reduction in the TCE source mass that is required to reach the dCULs is shown in Table 3.2.

Table 3.2. *Summary of Methods 1, 2 and 3.*

	% Reduction Needed	Weaknesses	Strengths
Method 1	94% in TCE 2016 Source Mass	Assumes source mass proportional to groundwater concentration; assumes 50% of mass has been removed (see Section 5)	Simple calculation
Method 2	66% in TCE 2016 Source Mass	May be affected by operation of original SVE system	Simple calculation
Method 3	97% in TCE 2016 source zone vapors	More complex calculation	Focuses on intermediate zone

As a conservative measure and relying on each method result to bracket the assumption, these percentage reductions in TCE were converted to minimum, most likely, and maximum values for reductions in TCE vapor concentrations for use in the restoration time frame calculation shown in Sections 4 and as a proxy for the approximate reduction in total VOC mass used in the restoration time frame calculation shown in Section 5. Factors such as the potential for concentration rebound, the exact nature of the relationship between TCE and VOC concentrations, and uncertainty in the input data are addressed by increasing the values estimated by Methods 1, 2, and 3 as shown below:

For the time frame method shown in Section 4:

- Required Performance: a 95% reduction in TCE vapor concentrations in the SVE effluent is needed (this is higher than Method 1)

For the time frame method shown in Section 5, the reduction in TCE from Table 3.2 was used as a proxy for the minimum, most likely, and maximum reduction in total VOC mass in Zone A as shown below:

Minimum Required Performance:	90% reduction in VOC mass in Zone A is needed	*This is a significant increase over the Method 2 value*
Most Likely Required Performance:	95% reduction in VOC mass in Zone A is needed	*This is higher than Method 1*
Maximum Required Performance:	99% reduction in VOC mass in Zone A is needed	*This is higher than Method 3*

During the period 2012 to 2014, the trendline for total VOC concentrations in the SVE effluent has been similar to the trendline for TCE in the SVE effluent, supporting the use of the TCE analysis as a proxy for the total VOC reduction requirements (see Appendix C.3).

The 90% to 99% range has been used at other SVE sites for reduction in vapor concentration thereby increasing the confidence in this approach (see Appendix A.1):

> *"For example, closure can be based on attaining a specific (e.g., 90 or 99%) reduction in effluent CVOC concentrations or mass-removal rates measured for the SVE system."* (Brusseau et al., 2013)
>
> *"Assessment of concentrations at vapor monitoring points is another viable approach (for use as a remediation goal). The EPA determined that a 90% drop from initial vapor*

*concentration was adequate groundwater protection at the Keystone landfill site in Pennsylvania" (*Truex et al., 2013).

Key Points

- Three methods were used to estimate the percent reduction in source mass that is required to reach dCULs. They indicated 66%, 94%, and 97% reductions in either source mass or soil vapor concentrations would be required to achieve dCULs.
- As a conservative measure, the minimum, most likely, and maximum value for the required source mass reduction used for the restoration time frame calculations were 90%, 95%, and 99%, respectively (Sections 4 and 5).

4.0 METHOD 1: VAPOR CONCENTRATION TREND EXTRAPOLATION

4.1 Description of Trend Extrapolation Method

Brusseau et al. (2013) described how a percentage reduction in soil gas concentrations can be used for closure: "*For example, closure can be based on attaining a specific (e.g., 90 or 99%) reduction in effluent CVOC concentrations or mass-removal rates measured for the SVE system.*"

TCE effluent vapor concentrations, from the startup of the Zone A SVE system in March 2012 to the most recent data collection in May 2017, were plotted against time and fit to an exponential curve. Concentrations are expected to decrease following an exponential decay model, as less vapor is available for removal the longer the SVE system runs (see **Appendix A.2** for background on declining concentrations from SVE systems). These best-fit exponential curves were then solved for the time it will take for the SVE system to reduce TCE concentrations by the percent reduction provided by the SVEET model in Section 3 (95% reduction) that will allow Zone A to reach groundwater draft clean up levels without operating the SVE system.

However, the period from March 2012 to May 2017 does not represent the fully operational SVE system, since the shallow and intermediate wells were temporarily shut off in late 2013, and operated intermittently from that point. Therefore, the decline in the SVE vapor concentrations may reflect operating the SVE system at a lower rate, rather than an actual decline due to true mass removal. To account for this possibility, the vapor concentration trend method was also repeated, but only using data from the initial 1.4 years of operation of the enhanced SVE system.

The two scenarios performed were:

- The **historic** performance scenario, based on March 2012 (t=0) to May 2017 (t = ~ 5.2 yrs). This scenario reflects the performance of the SVE system at a lower overall rate compared to the initial performance.
- The **initial** performance scenario, based on June 2012 (t=0) to November 2013 (t= ~1.4 yrs). This scenario reflects a higher removal rate.

One final step is to add in time for drums that may not have yet released their liquid contents. Five years were added to the calculated restoration time frame as conservative safety factor to account in the unlikely event that some drums that have not yet released their contents (see Section 2.3).

4.2 Results

Based on the **historic performance** scenario, if the SVE system is allowed to operate as it did from March 2012 to May 2017, the TCE restoration goal will be met in a predicted 18 years. If operation resumed in 2017, this would be 2035. If the SVE system is allowed to operate at **initial performance**, the restoration goal will be met in a predicted 15 years. If operation resumed in 2017, this would be 2032. These results are also presented in Table 4.1.

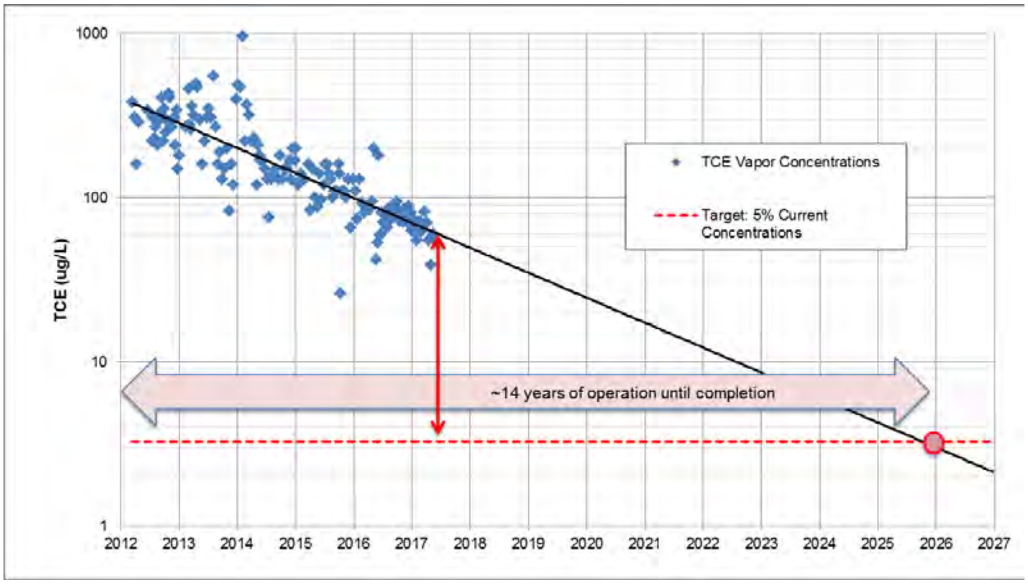


Figure 4.1. *Extrapolation of restoration time frame for the **historic performance** scenario for **TCE** vapor concentration. The period of time used for the high performance scenario is also highlighted in the top panel. Year 0 starts in March 2012 and the extrapolation starts in June 2017. Dates do not account for the nine year period for drums to release their contents.*

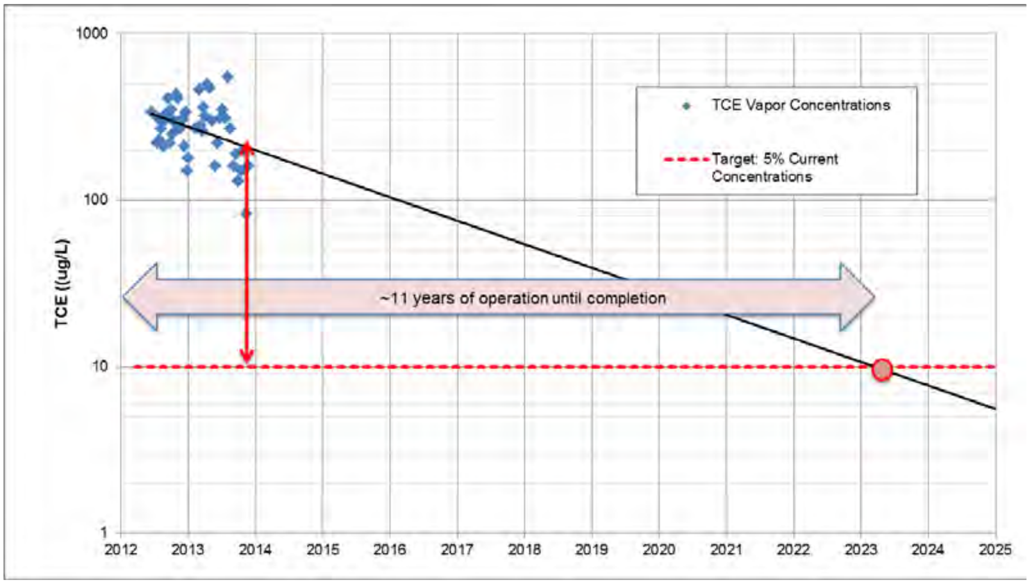


Figure 4.2. *Extrapolation of restoration time frame for **initial performance scenario** for **TCE**. Year 0 starts in March 2012 and the extrapolation starts in August 2013. Dates do not account for the nine year period for drums to release their contents.*

Table 4.1. *Time frame for restoration of TCE vapors at Zone A by soil vapor extraction.*

Scenario	TCE Vapor Concentration At Start of Extrapolation* (ug/L)	Percent Reduction in TCE Soil Vapor Needed**	Target TCE Vapor Concentration in SVE Discharge Needed to Reach dCULs (µg/L)	Total Remediation Time from 2012 (yrs)***	Total Remediation Time from 2017 (yrs)***
Historic Performance	65	95%	3.25	14+5=19	14
Initial Performance	200	95%	10	11+5=16	11

** From top of red arrows in Figures 4.1 and 4.2   ** From Section 3   *** From Figures 4.1 and 4.2 with five years added to account for the possibility that some drums that have not yet released their contents.*

Key Points

- The Trend Extrapolation Method was performed for TCE vapors discharged by the SVE system.
- Two different extrapolations were evaluated: overall system performance over 5.2 years from 2012 and performance only when the system was running at full operation for 1.4 years from 2012.
- Five years were added to the extrapolation results as a conservative safety factor to account for the possibility that some drums have not released their contents (see Section 2.3).
- The restoration time frame for TCE was calculated to be **14 years** from year 2017 (i.e., year 2031).

5.0 METHOD 2: BOX MODEL METHOD

5.1 Calculation Overview

The Box Model approach described in **Appendix A.3** was used to estimate restoration time frames for the Zone A SVE system. The calculations involve five steps, including two separate methods used to calculate the time frame:

Step 1. Estimate VOC Mass Emplaced in 1975
Step 2. Estimate VOC Mass Removed by SVE
Step 3. Estimate Mass Removed by Past Biodegradation
Step 4. Calculate Total Mass Removed to Date
Step 5. Estimate Time Frame Using Declining Rate Method

As a conservative measure, calculations did not account for two processes that could shorten the restoration time frame:

- Future biodegradation: although future biodegradation of petroleum solvents is assured, as they degrade both aerobically and anaerobically, this process was not included as a conservative measure.
- Historic release of mass to groundwater. There is no current estimate for this value. Overall, the intent of future SVE operation is to reduce this mass release to a level that meets dCULs.

The method is based on evaluating the entire source mass (not just TCE) and assumes the source mass will be decreasing over time as it is removed by the SVE system (see Appendix A.3). Key assumptions regarding the supporting information and input data for this method are explained in Tables 5.1, 5.2, 5.3, and 5.4.

5.2 Statistical Approach to Estimating Time Frames

To account for the uncertainty and range in input data, the Monte Carlo statistical approach (Appendix C) was used with the Box Model to estimate the statistics and probability of different restoration time frames. For example, a Monte Carlo analysis shows:

- the most likely (50th percentile) restoration time frame;
- the value where there is a 90 percent chance that the actual restoration time frame is equal to or less than that value (90th percentile);
- the entire statistical distribution of restoration time frames.

The Monte Carlo approach is applicable at the Pasco Landfill as a reliable means to address uncertainties in the data necessary for the estimation of restoration time frames, such as the quantity of VOCs in the buried drums, solvent composition of the VOCs, mass of Tentatively Identified Compounds (TICs) removed by the SVE, rate of biodegradation, and the drum breakage and release rate.

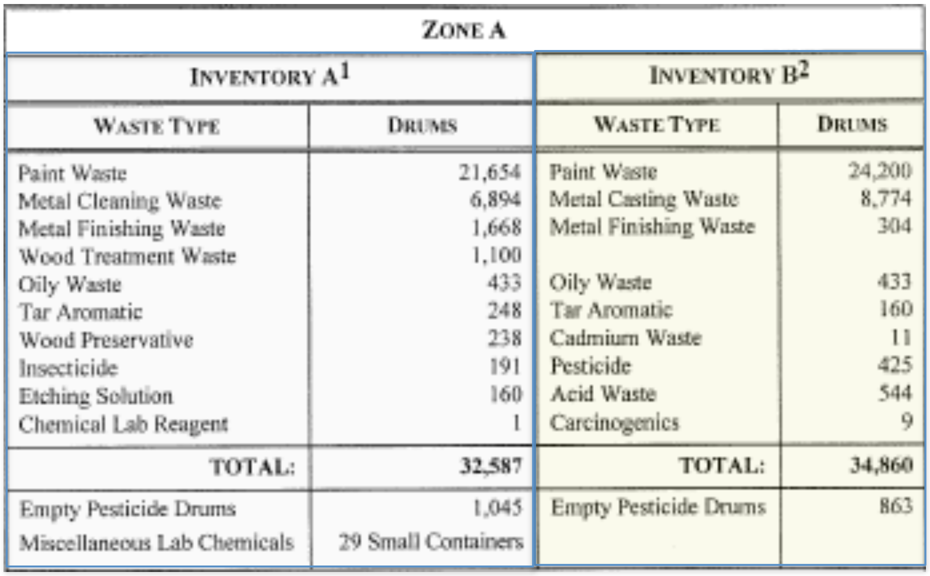
5.3 Restoration Time Frame Analysis

For this study, Monte Carlo analysis was performed using an Excel add-in (RiskAMP, 2014) (Appendix C). Input parameters for the Box Models are detailed in Tables 5.1 through 5.4 and summarized below. Rather than using a single value, triangular distributions were employed for parameters estimated with a range of values.

The Monte Carlo input data for each of the six steps is described below.

Step 1. Estimate VOC Mass Emplaced by 1975
VOC mass in 1975 was calculated as the product of the volume of liquids in drums that potentially contain VOCs, percent of solvents in the liquid, and density of the VOCs as described below. In estimating total VOC mass to be remedied by the SVE system, no allowance (reduction) was made for the liquid mass lost in the early 1970s from the approximately 10,000 initial, randomly-placed drums that were subsequently bulldozed to prepare for the stacked drums.

1. **Volume of liquids in drums that contain VOCs.**
   The total number of drums in Zone A from 1972 through mid-1975 was obtained from Inventory B2 from the Phase II Remedial Investigation Report (Philip, 1998). Each drum was assumed to be of standard 55-gal capacity. The total volume of liquids in the drums was calculated by simply multiplying the number of drums by the drum capacity and the assumed quantity of VOC in each drum (see Figure 5.1, Table 5.1).



ZONE A			
INVENTORY A[1]		INVENTORY B[2]	
WASTE TYPE	DRUMS	WASTE TYPE	DRUMS
Paint Waste	21,654	Paint Waste	24,200
Metal Cleaning Waste	6,894	Metal Casting Waste	8,774
Metal Finishing Waste	1,668	Metal Finishing Waste	304
Wood Treatment Waste	1,100		
Oily Waste	433	Oily Waste	433
Tar Aromatic	248	Tar Aromatic	160
Wood Preservative	238	Cadmium Waste	11
Insecticide	191	Pesticide	425
Etching Solution	160	Acid Waste	544
Chemical Lab Reagent	1	Carcinogenics	9
TOTAL:	32,587	TOTAL:	34,860
Empty Pesticide Drums	1,045	Empty Pesticide Drums	863
Miscellaneous Lab Chemicals	29 Small Containers		

Figure 5.1. *Drum inventory for Zone A (Phase II Remedial Investigation Report, Philip, 1998). Inventory B was used for this analysis*

2. **Percent of solvents in the liquid.**
   Composition of spent solvent still bottoms were based on literature estimations.[1,2] See Table 5.2.

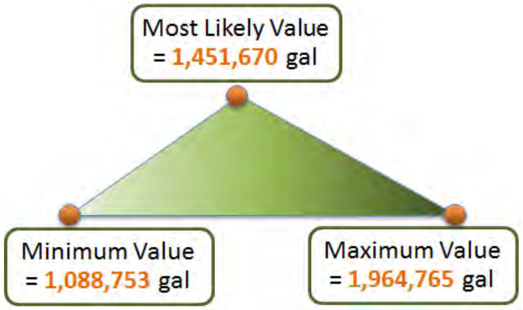
3. **Density of the VOCs.**
   The average of toluene and acetone densities, 6.8 pounds per gallon, were assumed to be representative of the VOCs in the Zone A drums given the predominance of those compounds in the overall source mass.

---

[1] USEPA, 1980: "Solvent recovery still bottoms (sludges) from contract reclaiming operations amount to … an average solvent content of about 25 percent….Depending on the recovery techniques, sludges which result from reclamation processes contain from 1 to 50% of the original solvent."

[2] USEPA, 1978: "The composition of such waste varies depending on the original use of the solvent. But up to 50 percent is unreclaimed solvent".

Table 5.1. *Step 1. Estimate VOC mass emplaced by 1975.*

Parameter	Value	Methodology
Parameter: *Volume Liquid in Drums that Contain VOCs* **Monte Carlo Distribution:** *Triangular*		- The **Minimum Value** assumes 1) casting waste (8774 drums), acid waste (544 drums), and cadmium waste drums (11 drums) do not contain VOCs (i.e., VOC volume is zero), and 2) drums are only 75% full. - The **Most Likely Value** assumes 1) casting waste, acid waste, and cadmium waste drums do not contain VOCs, and 2) drums are 100% full. - The **Maximum Value** assumes 1) all drums delivered to the site contain VOCs and are similar in composition to paint waste, and 2) all are 100% full. - All drums are assumed to be 55 gallon drums. - See Figure 5.1.
Parameter: *Percent Solvents* **Monte Carlo Distribution:** *Triangular*		- Initially, a **Minimum Value** of 5% was assumed based on a 1980 RCRA reported solvent content. However, this value resulted in negative mass numbers. Increasing the minimum to 10% (based on the USEPA (1978) estimate) also resulted in negative mass numbers. Therefore, based on a trial and error method a value of 15% was employed as the final minimum value. - The **Most Likely Value** was based on the average value reported by RCRA, 1990. - The **Maximum Value** was based on maximum solvent contents reported in literature. Data Sources: RCRA, 1980; Solvent Reclamation c4s07.pdf.; USEPA, 1978; USEPA, 1979.
Parameter: *VOCs Density* **Monte Carlo Distribution:** *None*	6.8 lbs/gal	Average density of two of the most common constituents, toluene and acetone. Data Source: literature.

Key Point: Monte Carlo analysis was used for parameters associated with uncertainty and range in input data. For these parameters, a triangular distribution requiring a minimum, most likely, and maximum value provided a better estimation of the input parameter than a single value.

Step 2. Estimate VOC Mass Removed by SVE

The total mass of VOCs removed by the SVE system from 1997 to July 2016 was obtained as described below.

1) **Total mass removed by SVE**
   Total mass removed by the SVE system was obtained from the SVE Sample Data (EPI, 2017). Because the SVE system was expanded in March 2012, estimates for mass removed were obtained prior to (from 1997 through March 2012) and post (March 2012 through May 2017) this date. See Table 5.2.

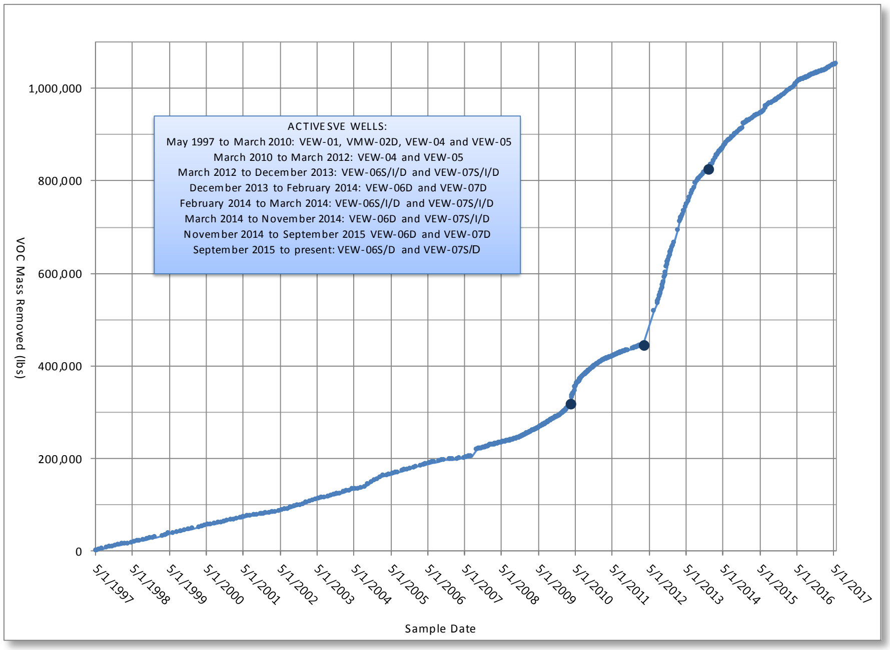
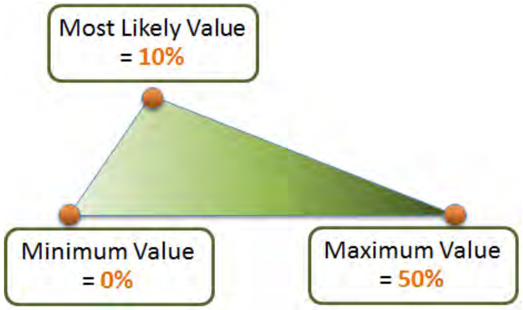


Figure 5.2. *SVE system cumulative VOC removal data from 1997 to May 2017 (EPI, 2017).*

2) **Mass of VOC TICs removed by SVE**
   TICs have been measured in the SVE vapor waste stream. A probabilistic estimate of mass removal reflected by TICs in the SVE system effluent gas was obtained by multiplying the percent of TICs in the VOCs by the total mass of VOCs removed by the SVE system to date (i.e., from 1997 through May 2017). See Table 5.2.

Table 5.2. *Mass removed by the SVE system input parameters.*

Parameter	Value	Methodology
Parameter: *VOC Mass Removed SVE 1997 - March 2012* **Monte Carlo Distribution:** *None*	445,000 lbs VOC removed	• Based on SVE operational records through March 5, 2012, the date the expanded SVE system became operational. Data Source: EPI, 2017.
Parameter: Total Mass Removed by SVE **Monte Carlo Distribution:** *None*	1,052,964 lbs VOC removed	• Based on SVE operational records through May 30, 2017. Data Source: EPI, 2017.
Parameter: Mass VOC Removed SVE March 2012 - May 2017 **Monte Carlo Distribution:** *None*	607,964 lbs VOC removed	• Obtained by subtracting the mass obtained in row 1 above (VOC mass removed by SVE *1997 - March 2012)* from row 2 above (total mass removed by SVE). • Based on SVE operational records through May 30, 2017. Data Source: EPI, 2017.
Parameter: *TICs/VOCs Removed SVE (%)* **Monte Carlo Distribution:** *Triangular*		• TICs accounting for 30-50% of the total VOCs were reported for the site. Data Source: Adams, 2016a. • As a conservative measure, the **Minimum Value** assumes no TICs are present (0%) • The **Most Likely Value (10%)** is a conservative measure taking into account the significant uncertainty in evaluating for TICs and is one fourth of the value reported by Adams (2016). • The **Maximum Value** is the upper end of the reported range (50%).

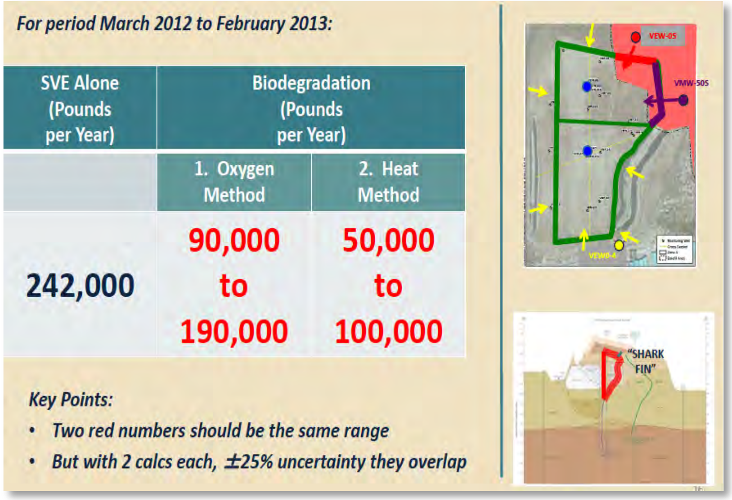
Step 3. Estimate Mass Removed by Past Biodegradation

The total mass removed by biodegradation between 1975 and 2016 was estimated as the sum of the mass biodegraded between 1975 and 2012, and the mass biodegraded between 2013 and 2016. The most prevalent VOC compounds in Zone A are readily biodegradable in both aerobic and anaerobic soils unless the temperatures are too cold (near freezing) or too hot (above 176° F); have unusual high or low pH levels (below 5 or above 8); or are very dry with low moisture content in the soils.

1) **Mass biodegraded between 1975 and 2012**
   Aromatics and ketones are hydrocarbons that are well known to be biodegraded aerobically and anaerobically Lyman et al., 1990; Howard et al., 1991; Wiedemeier et al., 1999). The mass of VOCs biodegraded between 1975 and 2012 was estimated by using typical Natural Source Zone Depletion (NSZD) rates at petroleum hydrocarbon sites by anaerobic processes (Palia, 2016, Garg et al., 2017) as a starting point. Because the majority of the gasoline components expressed as NSZD (primarily short- and long-chained alkanes) are less biodegradable than aromatics or ketones this rate should be conservative when applied to Zone A. The presence of NSZD processes occurring in Zone A prior to startup of the expanded SVE system in 2012 is supported by elevated groundwater temperatures downgradient of Zone A in the 1990s and 2000s, the depletion of oxygen in the subsurface by chemical reactions, and the ubiquitous nature of NSZD at almost every hydrocarbon site.

   The NSZD gallons per acre per year values were multiplied by the Zone A drum waste area, and the number of years over which biodegradation was assumed to have occurred (1975 through 2012). Because of the uncertainty in this 1975-2012 biodegradation term, the biodegradation rate was multiplied by a range of values with a most likely value of 50%. See Table 5.3.

2) **Mass biodegraded between 2013 and 2016**.
   Estimates of mass biodegraded between 2013 and 2016 were based on an analysis of the oxygen consumed and heat generated over the first ten months of the expanded SVE system operation (March 2012 to February 2013). See Figure 5.3 and Table 5.3.



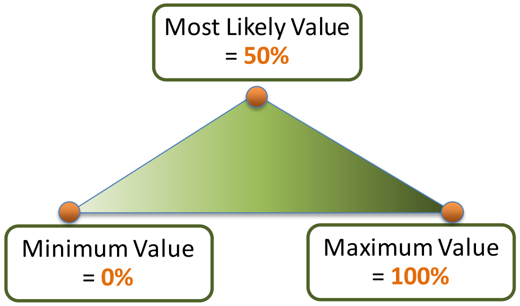
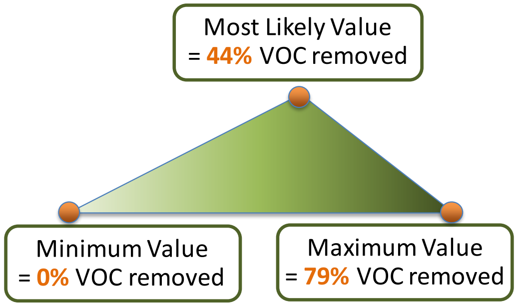
For period March 2012 to February 2013:

SVE Alone (Pounds per Year)	Biodegradation (Pounds per Year)	
	1. Oxygen Method	2. Heat Method
242,000	90,000 to 190,000	50,000 to 100,000

Key Points:
- *Two red numbers should be the same range*
- *But with 2 calcs each, ±25% uncertainty they overlap*

***Figure 5.3.** Amount of oxygen consumed and heat generated by expanded SVE system (GSI Environmental, 2013)*

Table 5.3. *Mass removed by biodegradation input parameters.*

Parameter	Value	Methodology
Parameter: *Biodegradation 1975-2012 Base Estimate* **Monte Carlo Distribution:** *None*	190,000 lbs VOC	Calculated based on: • Median NSZD rate of 700 gal/acre/year from Palia, 2016, • Source zone = area of 1.1 acres, and • Elapsed time of 36 years (from 1975 through 2011).
Parameter: *Uncertainty Factor* **Monte Carlo Distribution:** *Triangular*		• The **Minimum Value** (0%) assumes no biodegradation is occurring as a conservative measure. • The **Most Likely Value** assumes a 50% chance for occurrence of the 190,000 pounds of biodegradation during this period. • The **Maximum Value** assumes a 100% chance for occurrence of the 190,000 pounds of biodegradation during this period.
Parameter: *Biodegradation 2013-2016 Base Estimate* **Monte Carlo Distribution:** *Triangular*		• This parameter is the amount of biodegradation that occurred over three years expressed as a percent of the SVE removal rate. • Based on the analysis of the amount of oxygen consumed and heat generated data from the first ten months of expanded operation. • The **Minimum Value** assumes no biodegradation occurring as a conservative measure. • The **Most Likely Value** is the average of the estimated biodegradation shown in Figure 5.3 (i.e., average of 90,000, 190,000, 50,000, and 100,000 divided by 242,000 (mass removed by SVE system) equals 44% of the VOC mass removed by the SVE system). • The **Maximum Value** is the upper end of the estimated range (i.e., 190,000 in Fig. 5.23 divided by 242,000 or biodegradation during this period equals 79% of the VOC mass removed by the SVE system). Data Source: SVE system operation from March 2012 to February 2013.

Step 4. Calculate Total Mass Removed to Date

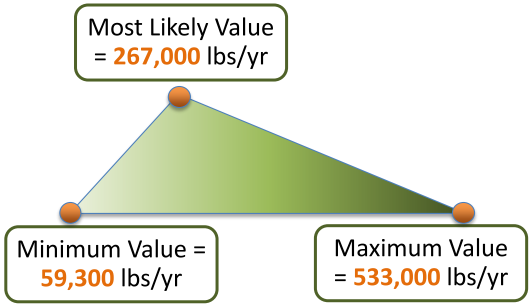
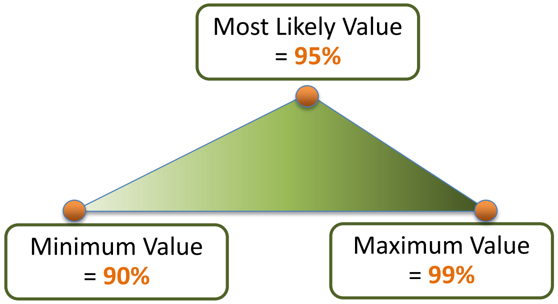
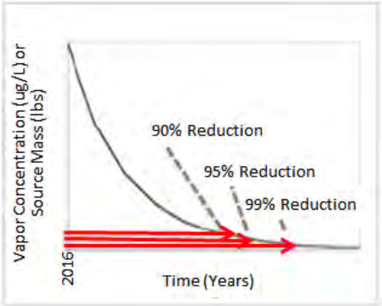
The total mass removed to date was estimated as the sum of masses obtained in Step 2 (mass removed by SVE) and Step 3 (mass removed by biodegradation) above.

Step 5. Estimate Time Frame Using Declining Rate Method

The decay method assumes a first order type source decay model, where the concentration of the extracted fluid is proportional to the mass remaining in the source (Appendix A.3). Therefore, the restoration time frame is reached when the concentration and mass reach a pre-determined percent reduction from starting conditions, which in this case is the year 2017. See Table 5.4 for key input data.

.

Table 5.4. *Restoration time frame input parameters.*

<table>
<tr><th>Parameter</th><th>Value</th><th>Methodology</th></tr>
<tr><td colspan="3">Time Frame - Simple Method</td></tr>
<tr><td>Parameter:
<i>Assumed Initial Mass Removal Rate – Future at System Startup</i>
Monte Carlo Distribution:
<i>Triangular</i></td><td> </td><td>• Based on the SVE system operational data.
• The Minimum Value was the amount removed by the SVE system from July 2015 to July 2016 when operational restrictions were in place: 59,300 lbs/yr (EPI, 2017)
• The Most Likely Value is the mass removed from 3/4/2012 through 3/5/2013 divided by the time interval of 1 year: 267,000 lbs/yr (EPI, 2017)
• The Maximum Value is based on the maximum removal rate specified in the air permit (64 lbs/hr) with an assumed SVE runtime of 95%: 533,000 lbs/yr. (Adams, 2016b).
• For the Declining Rate method, these rates decline as a first order decay curve.</td></tr>
<tr><td colspan="3">Time Frame - Decay Model</td></tr>
<tr><td>Parameter:
<i>Percent Mass Reduction in Removal Rate to Reach dCULs; this is used as endpoint for the Declining Rate Method</i>
Monte Carlo Distribution:
<i>Triangular</i></td><td> </td><td>• Based on results from Section 3:
• The Minimum Value assumes a 90% reduction in total VOC source mass will be required to meet dCULs.
• The Most Likely Value assumes a 95% reduction will be required.
• The Maximum Value assumes a 99% reduction will be required.
 </td></tr>
</table>

One final step is to add in time for drums that may not have yet released their liquid contents. Five years were added to the calculated restoration time frame as conservative safety factor to account in the unlikely event that some drums that have not yet released their contents (see Section 2.3).

5.4 Box Model Results

Fraction of Total VOC Mass Removed to Date from Zone A by SVE System and due to Biodegradation

- Most Likely Value: 53%.
- 90% chance this value is equal to or greater than 36% of the initial VOC mass.

VOC Mass Removed to Date by SVE System and due to Biodegradation

- Most Likely Value: 1,500,000 pounds.
- 10% chance value is equal to or greater than 1,800,000 pounds.

VOC Mass Remaining in 2017

- Most Likely Value: 1,400,000 pounds.
- 10% chance value is equal to or greater than 2,650,000 pounds.

Time Frame – Declining Rate Method

- Most Likely Restoration Time Frame: 16 years (includes five years to account for drums yet to fully release their flowable contents).
- 10% chance Restoration Time Frame is greater than 33 years.

Key Points

- The Monte Carlo analysis suggests a little over half of the VOC mass has been removed from the source as of July 2016.
- Assuming a declining removal rate, a most likely restoration time frame of 16 years from 2017 was calculated. There is a 10% chance the restoration time frame is 33 years or more.

6.0 CONCLUSIONS

Drum Integrity and Release of Flowable Liquids

Two drum failure models that project the probability of corrosion failure in retrievably stored drums at DOE sites were applied to the drums emplaced at Zone A. Two types of corrosion failures were modeled: pitting/corrosion failures and structural integrity failures.

Key Point: All Zone A drums have likely started leaking by now. As a conservative measure, five years have been added to both restoration time frame calculation methods.

Supporting Information: The higher rates of subsidence in Zone A observed starting in 2012 matches the time when the drum failure models predicts the beginning of structural failure for drums not in direct contact with soil.

Required Mass Removal to Reach Draft Cleanup Standards

Three methods were used to estimate the percentage reduction in VOC soil vapor (or its linearly related parameter, VOC source mass) that is required to meet dCULs.

Key Point: Between 90% and 99% reduction will be required to meet dCULs. A 95% reduction is the most likely value.

Supporting Information: Two methods are based on historic concentrations in groundwater. The third method, the SVEET tool was largely developed from experiences at the Hanford Site.

Restoration Time Frame Method 1

Zone A TCE concentration in the SVE discharge vs. time were plotted two ways to obtain trend lines used to determine an endpoint for the SVE system.

Key Point: This method indicated the restoration time frame is **14 years from now** (including five years to account for drums that may not have yet fully released their contents).

Restoration Time Frame Method 2

A statistical method based on a declining SVE source over time and entering minimum, most likely, and maximum values for key input data was used to estimate the Zone A restoration time frame.

Key Point: Assuming a declining SVE removal rate over time using a statistical calculation method, the most likely restoration time frame is **16 years from now**. There is a 10 percent chance the restoration time frame is 33 years or greater. Both these time frames include five years to account for drums that have yet to fully release their contents.

Supporting Information: Restoration time frame Methods 1 and 2 used two very different approaches to estimate restoration time frame. However, both methods provide generally the same result of restoration time frames of 14 years and 16 years, respectively, increasing the reliability of the predictions.

Rebound Testing

Rebound testing is recommended when the SVE system approaches the calculated restoration time frame endpoints, as is the usual course of action for SVE system evaluation and termination. The data from the rebound test intervals will update and provide more accurate information on the restoration time frame at that time.

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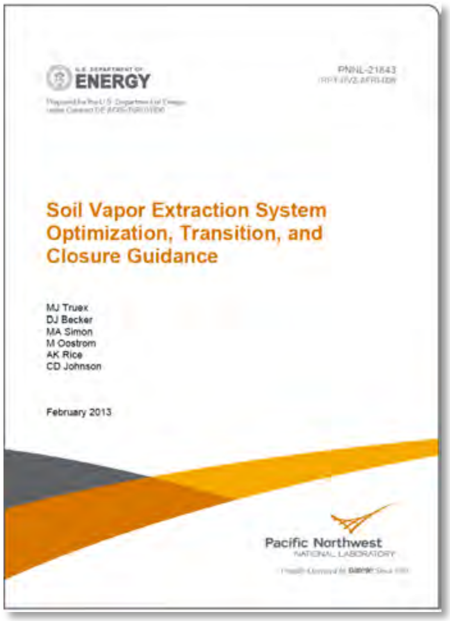
APPENDIX A. SVE RESTORATION TIME FRAME BACKGROUND INFORMATION

A.1 When is it Appropriate to Shut Down (Discontinue Operation) an SVE System?

To estimate restoration time frame for an SVE system, it is necessary to know when the system can be shut off through a series of rebound tests. Two recent technical publications, products of the Dept. of Energy's Deep Vadose Zone-Applied Field Research Initiative and the Dept. of Defense's Environmental Security and Technology Certification Program, describe key processes and considerations for restoration time frame and related issues (Truex et al., 2013, referenced as [1] below; Brusseau et al., 2013, referenced as [2] below). The authors include academics, researchers from National Research Laboratories, and SVE experts from the U.S. Environmental Protection Agency (USEPA) and the U.S. Army Corps of Engineers (USACE). Both documents rely on the authors' experience with SVE systems, in particular, a large SVE system at the Hanford Site (their "Base Case"), to describe the behavior of SVE systems over the lifecycle of the project. While Brusseau et al. (2013) focus on chlorinated solvent-dominated SVE systems, many of the concepts they describe are also applicable to sites with mixtures of hydrocarbons and chlorinated compounds such as Zone A.



U.S. DEPARTMENT OF
ENERGY

PNNL-21843

Soil Vapor Extraction System Optimization, Transition, and Closure Guidance

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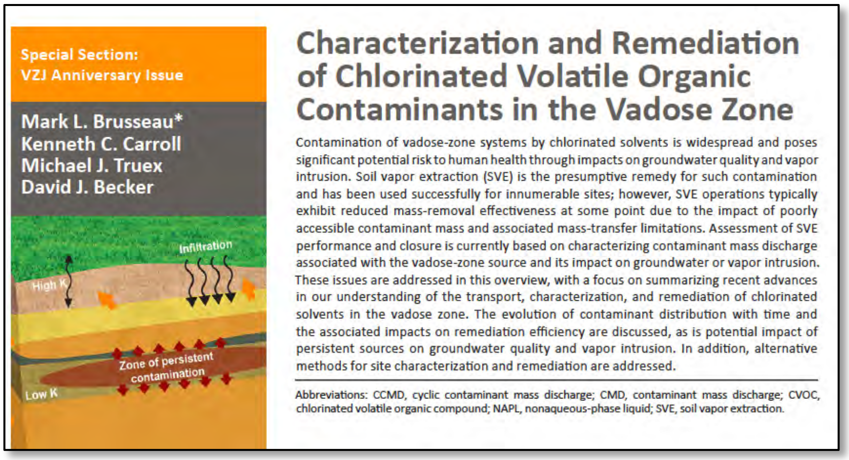
February 2013

Pacific Northwest
NATIONAL LABORATORY



Special Section:
VZJ Anniversary Issue

Mark L. Brusseau*
Kenneth C. Carroll
Michael J. Truex
David J. Becker

Characterization and Remediation of Chlorinated Volatile Organic Contaminants in the Vadose Zone

Contamination of vadose-zone systems by chlorinated solvents is widespread and poses significant potential risk to human health through impacts on groundwater quality and vapor intrusion. Soil vapor extraction (SVE) is the presumptive remedy for such contamination and has been used successfully for innumerable sites; however, SVE operations typically exhibit reduced mass-removal effectiveness at some point due to the impact of poorly accessible contaminant mass and associated mass-transfer limitations. Assessment of SVE performance and closure is currently based on characterizing contaminant mass discharge associated with the vadose-zone source and its impact on groundwater or vapor intrusion. These issues are addressed in this overview, with a focus on summarizing recent advances in our understanding of the transport, characterization, and remediation of chlorinated solvents in the vadose zone. The evolution of contaminant distribution with time and the associated impacts on remediation efficiency are discussed, as is potential impact of persistent sources on groundwater quality and vapor intrusion. In addition, alternative methods for site characterization and remediation are addressed.

Abbreviations: CCMD, cyclic contaminant mass discharge; CMD, contaminant mass discharge; CVOC, chlorinated volatile organic compound; NAPL, nonaqueous-phase liquid; SVE, soil vapor extraction.

The two documents present a number of important points that are relevant to a restoration time frame analysis of the Zone A SVE system.

SVE Conceptual Site Models (CSM):

> *"The fate of the contaminant mass also depends on processes that degrade or transform the contaminant. For example, petroleum hydrocarbons can biodegrade and some chlorinated ethanes (such as 1,1,1-trichloroethane) can undergo significant abiotic hydrolysis. These processes need to be at least qualitatively understood for a useful CSM."*[1]
>
> *"Normally, the mass removal rates decrease along a first-order (exponential) decay curve with high initial rates."*[1]

SVE Operations and Mass Removal Effectiveness

> *"A diminishing rate of contaminant extraction over time is typically observed due to 1) diminishing contaminant mass, and/or 2) slow rates of removal for contamination in low-permeability zones."*[1]

> *"The impact of source-zone dynamics on remedial actions is such that, typically, rates of mass removal or reduction slow with time, eventually reaching a point at which the operation becomes ineffective."*[2]
>
> *At some point, effluent concentrations and mass-removal rates start to decline, at first relatively rapidly and ultimately asymptotically, to significantly lower values."*[2]
>
> *"Inspection of the data reveals that mass-removal rates decreased by approximately 1.5 to three orders of magnitude during the operation period."*[2]

SVE Life Cycle and Asymptotes

> *"The relationship between source-zone status in the vadose zone and SVE operation is illustrated in Fig. (1.3), which depicts the typical three main stages of the life cycle of a contaminated site undergoing SVE remediation."*[2]
>
> **"***The onset of asymptotic, low-concentration conditions and other changes in these parameters may denote progression through the life cycle depicted in [Fig. A.1]"*[2]

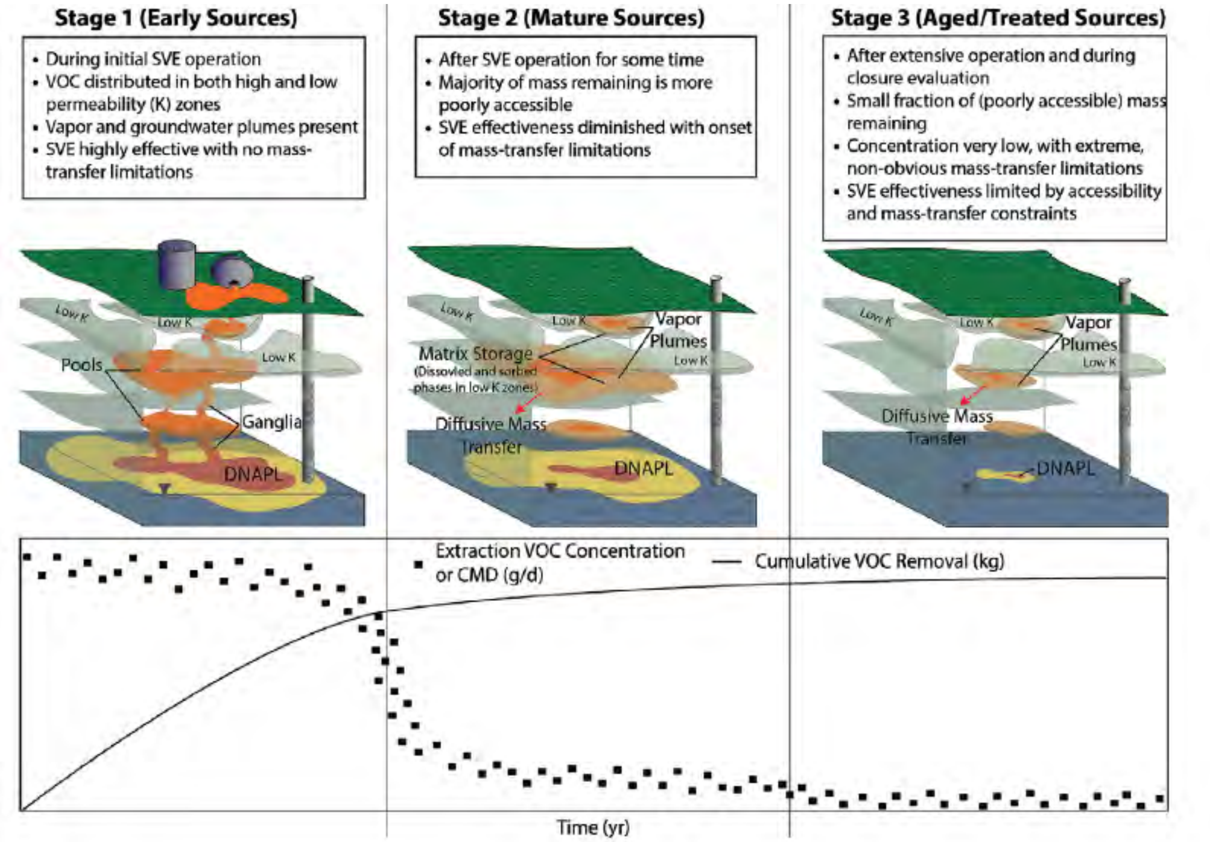


Figure A.1. *Conceptual diagram illustrating remediation issues and concentration-time and mass-removal-time profiles for the three stages typical to soil vapor extraction (SVE) remediation of sites contaminated by chlorinated volatile organic compounds (CVOCs). (Brusseau et al., 2013). "At some point, effluent concentrations and mass-removal rates start to decline, at first relatively rapidly and ultimately asymptotically, to significantly lower values."*

Assessing SVE Performance

"The measurement of operational parameters from the SVE system provides important information that was not necessarily available during initial site characterization on both the subsurface conditions and the strength and location of remaining contamination sources."[1]

"Mass removal from individual extraction wells and as an overall system is described in the foregoing paragraphs, and is a primary—though somewhat qualitative—line of evidence regarding the location and strength of remaining contamination."[1]

"In addition, contaminant mass discharge is also now recognized as a key metric for assessing remediation performance. Contaminant mass discharge is a measure of both mass removal from the source zone (illustrative of source longevity) and mass delivery from the source zone to the vadose zone (potential impact to soil gas and groundwater)."[2]

Use of Screening Models

"In lieu of advanced models, methods using simpler models, often termed screening models, can be used to estimate contaminant concentrations or contaminant mass discharge."[2]

"An approach that incorporates the analysis of SVE operations data, implementation of CMD (Contaminant Mass Discharge) tests, and mathematical modeling provides a flexible means to produce such information."[2]

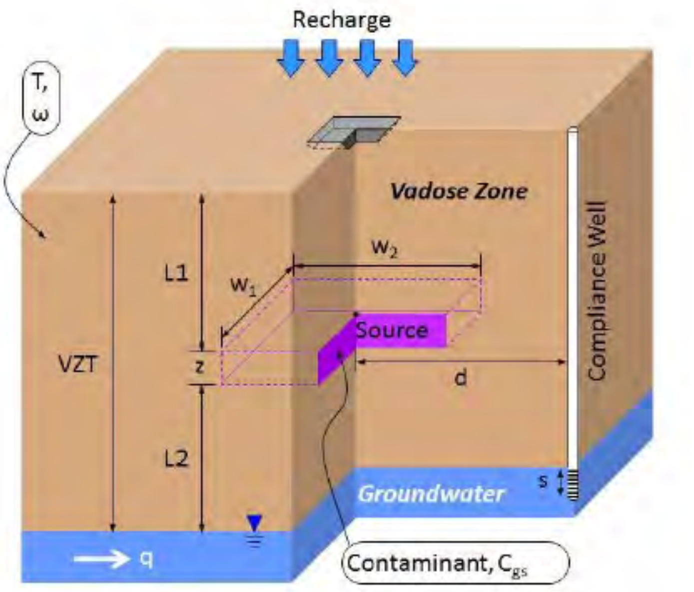
Type of SVE Remediation Objectives

"One approach is to calculate the maximum VOC mass flux from soil into the groundwater whereby concentrations in the groundwater would be below regulatory maximum contaminant levels. This approach was applied at the Tucson International Airport Site (USEPA, 2004)."[1]

"For example, closure can be based on attaining a specific (e.g., 90 or 99%) reduction in effluent CVOC concentrations or mass-removal rates measured for the SVE system."[2]

"Sampling can be conducted to determine if the soil gas at a site is below a specified cleanup value. EPA calculated the equilibrium vapor concentration with the maximum contaminant levels for comparison of sampling results at the Del Amo Site in California, an EPA Region 9 Superfund Site (USEPA, 1999)."[1]

"Assessment of concentrations at vapor monitoring points is another viable approach (for use as a remediation goal). The EPA determined that a 90% drop from initial vapor concentration was adequate groundwater protection at the Keystone landfill site in Pennsylvania (USEPA, 2000)."[1]



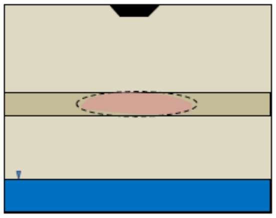


Figure A.2. *Top Figure: Conceptual model framework for impact to groundwater impacts. Bottom Figure: SVE Conceptual Site Model with "simple layered subsurface." (Truex et al., 2013).*

Types of SVE Sites

"Type I sites have contaminant source(s) remaining in the vadose zones with only low level dissolved phase contamination in the groundwater such that contaminant mass transfer in the area of the vadose zone source is from the vadose zone to the groundwater."[1]

"The Base Case represents an arid vadose zone for which this type of approach may be appropriately applied, for instance at the DOE Hanford Site (Carroll et al., 2012; Oostrom et al, 2007; Truex et al., 2012). For the simulations, it is assumed that the remaining persistent source zone [is] vertically in the middle of the vadose zone."[1] *(See Figure A.2).*

Relationship Between Key Variables

"The contaminant mass discharge reduction (CMDR) as a function of the mass reduction (MR) is a reflection of source conditions and of mass-transfer processes occurring within the system. Thus, this relationship serves as a defining characteristic for a given system and is useful for analysis and interpretation of mass removal behavior and the assessment of remediation performance."[2]

"An illustration of a CMDR–MR relationship is presented in Fig. (A.3) for Verona site."[2]

"Over the implied ranges, the compliance well concentrations showed proportionality (or inverse proportionality) with source concentration, Henry's Law constant, and well screen length."[1]

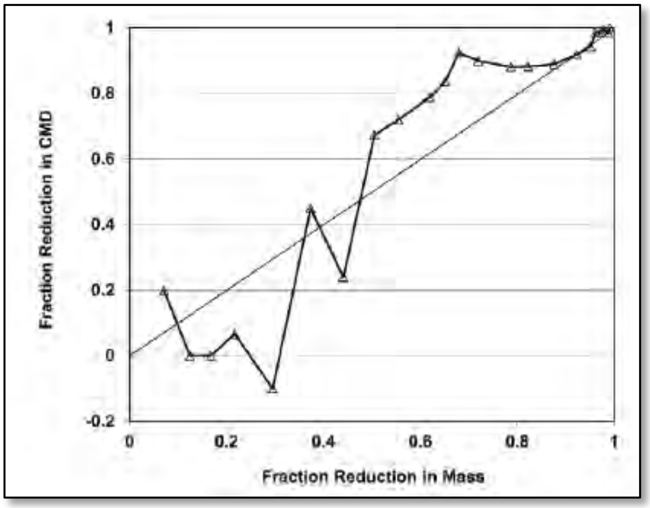


Figure A.3. *Relationship between reduction in mass removal (also called contaminant mass discharge or CMD) and reduction in contaminant mass for the Verona soil vapor extraction operation. The 1:1 line is shown for reference. (Brusseau et al., 2013.)*

Key Points

- To estimate restoration time frame for an SVE system, it is necessary to know when the system can be shut off following typical SVE rebound testing. Two recent publications "clarify and focus on the specific actions and decisions related to SVE optimization, transition, and/or closure" and provide important information for a Zone A SVE restoration time frame analysis.
- The documents state that SVE removal diminishes over time, degradation processes must be understood, and mass removal data ("contaminant mass discharge" or CMD) can be used to estimate source strength.
- An SVE system will go through a life cycle, ending with an asymptotic behavior of concentrations and mass removal demonstrated through a number of shut down-rebound tests.
- A variety of approaches have been used to determine when SVE systems can be shut down. Several have been adapted for this report: linking SVE performance to groundwater concentrations (**Section 3, Section 5**); assuming mass removal is correlated to mass remaining (**Section 3**); and reducing soil gas by a percentage reduction (**Section 4**).
- Using an SVE system at the Hanford Site as a foundation, the SVE Endpoint Tool (SVEET) was developed to help site stakeholders determine when an SVE system can be shut down. SVEET was adapted for this Zone A study as a supporting calculation (**Section 3**) for two different restoration time frame estimates.

A.2 SVE System Performance

A review of SVE performance at other sites can provide insights on performance and restoration time frame projections for the Zone A SVE system. Brusseau et al. (2013) compiled mass removal data from five multi-year SVE systems. As shown in Figure A.1, mass removal rates do diminish over time, with each system achieving at least one order of magnitude (90%) reduction in mass removal rate over a 52-month operational period starting in March 2012.

Brusseau's analysis includes a well-known SVE system at the Hanford Site's Plutonium Finishing Plant that has been removing carbon tetrachloride for over twenty years. The system was shut down in 2016, with the project manager stating,

> *"Ninety-one percent of the 80,000 kilograms of carbon tetrachloride that have been removed to date were removed in the first five years of operation," said Mark Byrnes, project manager for contractor CH2M HILL Plateau Remediation Company. "The last 18 years have been spent removing that last nine percent, but that's typical of this method. As contamination is removed from the soil, the concentrations go down and the time necessary to remove additional contaminants increases." (Energy.gov, 2016).*

The Hanford SVE system has some important parallels and differences to the Zone A SVE system (Table A.1):

Table A.1. *Similarities and differences between Zone A and Hanford Site SVE systems.*

Similarities	Differences
• Similar site hydrogeology (arid site, deep vadose zone, fast groundwater underlying site).	• VOC recovery by SVE at Zone A (over 1,000,000 pounds) has been much greater than the Hanford SVE system (180,000 pounds).
• Similar source stratigraphy (high concentrations of VOCs in a lower permeability zone near middle of vadose zone).	• Zone A VOCs primarily ketones and aromatic solvents which are aerobically biodegradable; Hanford's carbon tetrachloride is not aerobically biodegradable.
• Impact to groundwater is from chlorinated VOCs (carbon tetrachloride for Hanford, TCE for Zone A).	• Hanford does not contain any biodegradable materials which can elevate heat; Zone A contains biodegradable solvents (and potentially mixed debris).

In Figure A.4, Zone A shows a relatively stable mass removal rate over the first 30 months (starting in March 2012) compared to the Hanford system. This is likely because of the large VOC mass that was emplaced at the zone, estimated to be over 2 million pounds of VOCs (Section 5.3 and Appendix C) compared to the 200,000 pounds total removed at Hanford over the life of its SVE system. The mass removal rate does decrease significantly in Zone A from month 30 to month 52, but this is likely because the high-concentration intermediate zone SVE wells have not been used since month 30.

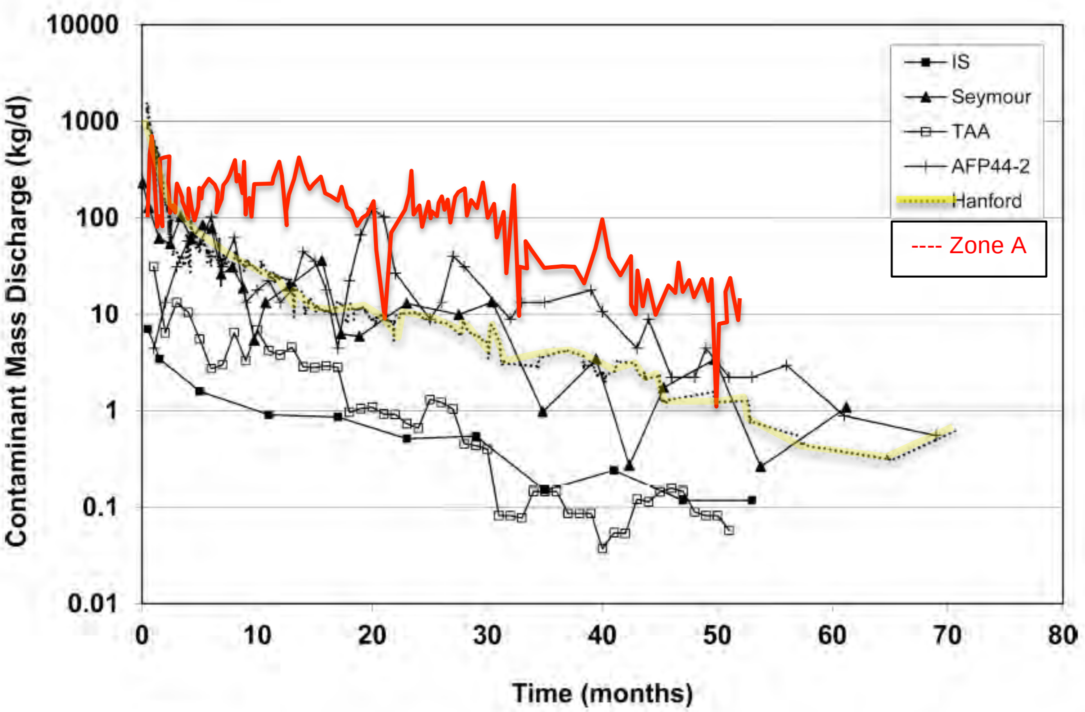


Figure A.4. *Mass removal rate vs. time for several multi-year SVE operations (Brusseau et al., 2013). Time represents operational time (periods of non-operation removed for all but Zone A). Zone A time period: March 2012 to July 2016. The down spike in Zone A mass removal rates at month 20 is due to curtailed operations after December 2013. Note the mass removal data are plotted on a semi-logarithmic scale, so every grid line represents a factor of 10.*

Truex et al. (2013) state that well and system mass removal rates are a primary ("but somewhat qualitative") line of evidence for understanding the strength of the remaining source. The system total mass removal rate and cumulative mass removal rate for the Hanford carbon tetrachloride SVE system that started operations in 1992 is shown in Figure A.5. The cumulative mass removal curve (yellow highlight) is "S shaped" with a slow start, followed by rapid increase in cumulative removal, then a subsequent shallowing out as the accessible mass has been removed. After 1996, the system was operated on and off until 2016, when the cumulative removal was about 80,000 kg of carbon tetrachloride. About 91% of the mass was removed during the first five years of operation, with the last 9% being removed over the most recent 18 years (Energy.gov, 2015; 2016).

In summary, the experience of the Hanford carbon tetrachloride SVE system has these lessons for Pasco (Energy.gov, 2015; 2016). :

- Mass removal rates from the Zone A SVE system will show a continuous decline at some point, and that process should be included in the restoration time frame calculation.
- The Hanford SVE system was operated for 23 years.

- About 91% of the total amount of contaminant mass removed at Hanford was removed in the first five years of operation, and 9% removed over the subsequent 18 years.
- The mass removal rate was reduced by about 99.9% over a five year period (Figure A.4).

In Section 4.0, the normalized cumulative mass removal rates were plotted for all six Zone A SVE wells to determine if any depicted the indication of an “S” shaped curve. Shapes of the six curves were analyzed to provide estimates of restoration time frame for individual mass areas and for Zone A overall.

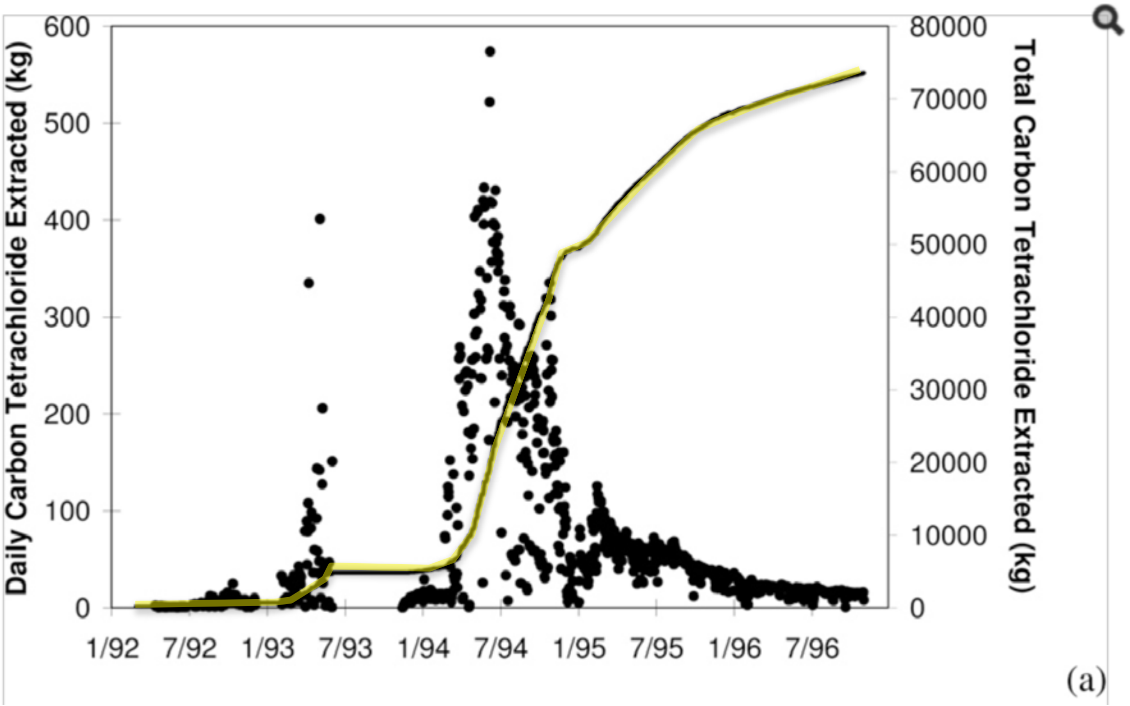


Figure A.5. *Mass removed and cumulative mass removal vs. time for the Hanford carbon tetrachloride SVE system 1992-1996 (Brusseau et al., 2010). The system was not operated during much of 1993. Cumulative mass removal depicted in the solid line (highlighted yellow), while daily mass extracted is represented in dots.*

Key Points

- The Hanford Site carbon tetrachloride SVE system has some important similarities and differences with Zone A. It was operated for 23 years, with 91% of the total mass removed during the first five years of operation.
- Mass removal rates typically diminish over time; for example, at the Hanford site, 91% of the mass was removed during the first 25% of operation time. The diminishing removal rate vs. time phenomena can make restoration time frames longer, and was accounted for in the restoration time frame calculations presented in **Sections 4 and 5.**
- Cumulative mass removal over time for individual SVE wells and the entire system are lines of evidence for determining remaining source strength. This concept was used to make restoration time frame calculations in **Section 4.**

A.3 Restoration Time Frame Methods

Two common methods to estimate restoration time frame are box models and extrapolating concentration trends. These methods were applied to this analysis to provide two relatively independent lines of evidences for estimating the restoration time frame for the Zone A SVE system.

Box Models

A box model method is a screening method that assumes the source zone contains a certain mass of removable contaminants, and that this mass is removed according to a specific pattern. Examples of this type of model are used in several environmental models (such as USEPA's BIOSCREEN (Newell et al, 1996), BIOCHLOR (Aziz et al., 1999), REMCHLOR (Falta et al., 2005) and REMFuel (USEPA, 2012), and the U.S. Air Force's SourceDK tool (Farhat et al., 2004) and described in other references such as Newell and Adamson (2005). Screening models are also referenced in Brusseau et al. (2013); see **Section A.2**.

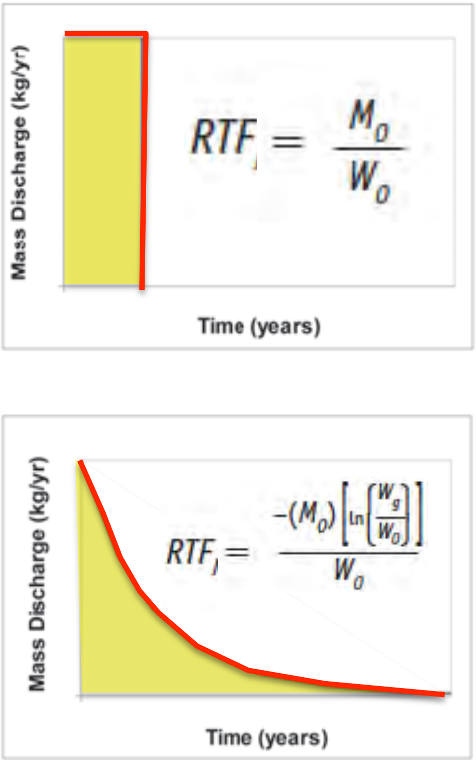


Figure A.6. *Box Model approach used with Simple Method (Top) and Declining Rate Methods (Bottom) with restoration time frame formulas. RTF: Restoration time frame. M_o: mass in box at time 0. W_o: mass removal rate at time 0. W_g: mass removal rate goal.*

There are several mass removal patterns that can be applied, ranging from simple formulas to complex mathematical functions. For the time frame analysis in this report, two patterns were used:

- "Simple Method" where the removal rate in the future is assumed to be constant throughout the lifetime of the SVE remediation system (Figure A.6). This method is commonly used because it is simple, but does not account for the declining rate of removal that is commonly observed in SVE and other environmental remediation systems.

- The "Declining Rate Method" where the removal rate is assumed to be proportional to the mass remaining in the box (Figure A.6). For example, if 50% of the mass in the box is removed, the soil gas concentration and the mass removal rate is reduced by 50% compared to the initial rate. This type of declining model is a first order (exponential) decay curve as described by Truex et al. (2013) and depicted in Figure A.4 from Brusseau et al. (2013).

As can be seen in Figure A.6, the Declining Rate Method results in longer restoration time frames, but as shown in **Section A.2**, is more realistic. One important part of applying the Declining Rate Method is that an endpoint is needed, such as the reduction of the initial remediation rate by some percentage. This percentage can be determined as a pre-defined percentage, e.g., "remove 90% of the initial mass", or by linking the required mass removal to a soil gas/groundwater concentration model such as SVEET.

The Box Model approach was applied to Zone A as described in **Section 5** because it provides a quantitative restoration time frame analysis based on mass estimates, removal rates, and other factors.

Trend Extrapolation Method

Extrapolation Methods plot existing concentration vs. time data and then using a best fit line, extrapolating the trend to that point in the future where the concentration goal is achieved. Because many environmental data have a log-normal statistical distribution, a semi-log graph is often used. The SourceDK tool has a module to enter groundwater concentration vs. time data and determine when the trend will cross a cleanup standard; Figure A.7 shows an example of the Trend Extrapolation Method. The Trend Extrapolation Method was applied to the Zone A SVE system as described in **Section 4** because it is a robust and relatively simple method that does not require large amount of input data.

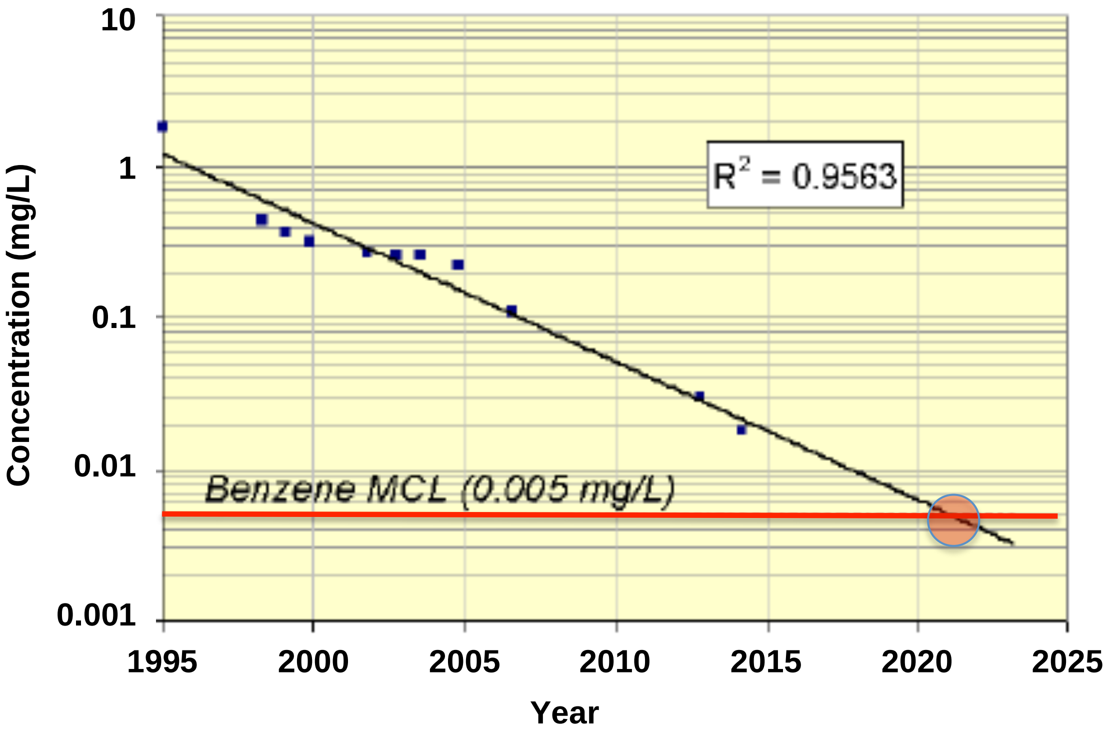


Figure a.7. *Example of trend extrapolation method for groundwater from the SourceDK tool. In this example the restoration time frame is about the year 2021.*

Key Points

- Two different restoration time frame approaches were used at Zone A: Box Model (Section 5) and Extrapolating Soil Gas Trends (Section 4).
- By using two relatively independent methods, the confidence in the end result will be increased if the methods result in similar restoration time frames.
- For the Box Model method, two sub-methods were employed: Simple Method assuming a constant VOC removal rate in the future, and the Declining Rate Method where the SVE removal rates decline in proportion to the remaining mass. The Declining Rate Method is likely more accurate than the Simple Method.

APPENDIX B. SITE SPECIFIC VALUES FOR MODEL INPUTS

B.1. Method 1: TCE Concentration in 1995 vs dCUL

Pre-remediation groundwater concentrations at Zone A were evaluated to provide a line of evidence regarding the approximate overall mass removal required to reach dCULs. This simple method is based on the concepts shown in Table B1.1.

Table B1.1. *Underlying concepts for historical groundwater analysis method.*

Underlying Concept	Technical Basis
Mass discharge from the soil to groundwater controls the groundwater concentrations.	*"One approach is to calculate the maximum VOC mass flux from soil into the groundwater whereby concentrations in the groundwater would be below regulatory maximum contaminant levels. This approach was applied at the Tucson International Airport Site (EPA 2004b)." (Brusseau et al., 2013; see Section 1.2).*
Mass discharge from the soil is directly related to the remaining soil mass.	*"The contaminant mass discharge reduction (CMDR) as a function of the mass reduction (MR) is a reflection of source conditions and of mass-transfer processes occurring within the system. Thus, this relationship serves as a defining characteristic for a given system and is useful for analysis and interpretation of mass removal behavior and the assessment of remediation performance." (Brusseau et al., 2013; see Section 1.2 and Figure 1.5).* See also screening model papers such as: Newell and Adamson, 2005; Newell et al., 1996; Falta et al., 2005.
Need groundwater concentrations that are relatively unaffected by remediation activities.	Data from 1995 represents site conditions before operation of the initial SVE system and before startup of the NoVOCs groundwater system. Wells EE-2 and EE-3 represent the wells closest to Zone A.

Overall, the method assumes that a 97% reduction in the 1995 mass at the site will reduce the groundwater concentrations at the edge of the waste in Zone A by 97%, the same percent reduction. While approximate, the method has the advantage of being easy to perform and is based on empirical data and does not require the use of a mass estimate.

For this Supporting Method calculation, the 1995 groundwater concentration for TCE was determined and compared to the 2.5 ug/L dCUL for TCE as shown below:

- dCUL for TCE: 2.5 ug/L
- 1995 representative TCE groundwater concentration: 85 ug/L

% reduction in concentration required to achieve the dCUL: $100 - \left(\frac{2.5}{85}\right) \bullet 100 = \ 97\%$

Based on underlying concepts, ~97% of mass present in 1995 is required to be removed to achieve dCULs. For example, if there were 100,000 lbs of TCE initially present in the subsurface, then this mass would have to be reduced to about 3,000 lbs to reach dCULs. However, about 50% of the VOC mass was estimated to have been removed by biodegradation and SVE since 1995 (see Section 5). Therefore, factoring in this removal, a **94% reduction** in the current mass would be required to achieve the reduction from 50,000 (half of 100,000) lbs to

3,000 lbs and meet the dCULs. This method assumes the removal rate for TCE is similar to the removal rate for all VOCs.

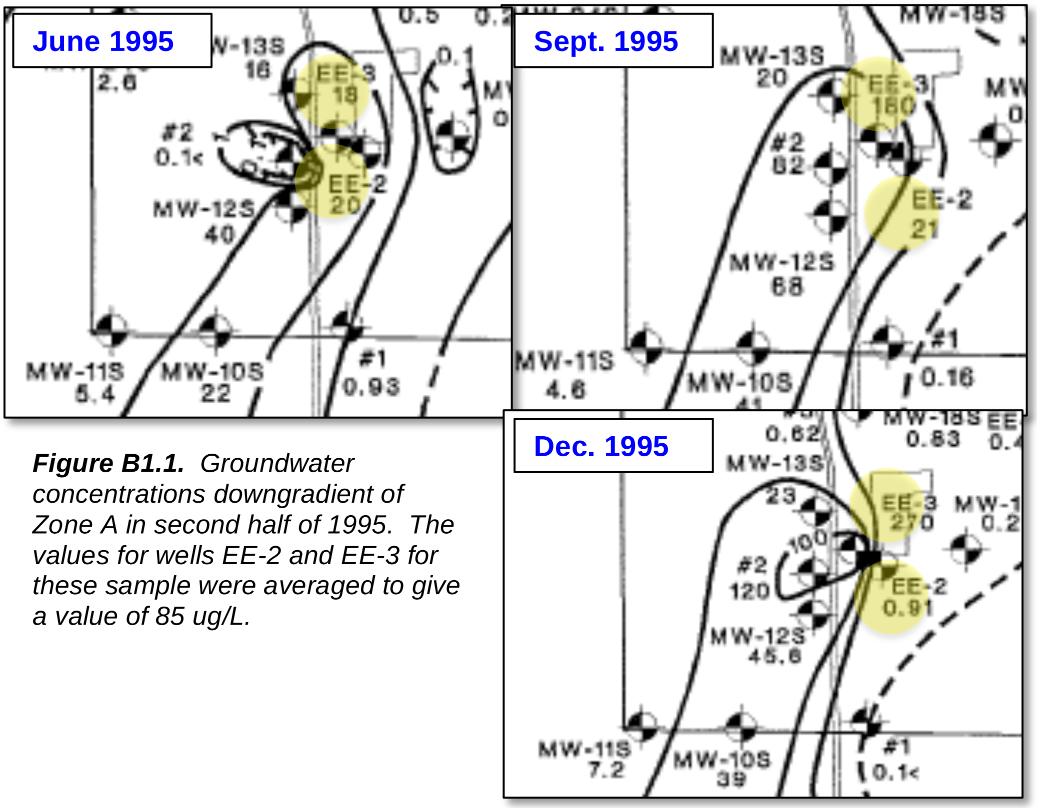


Figure B1.1. *Groundwater concentrations downgradient of Zone A in second half of 1995. The values for wells EE-2 and EE-3 for these sample were averaged to give a value of 85 ug/L.*

B.2. Method 2: TCE Concentration in 2011 vs. dCUL

Based on SVE operational records, the system was running but not at full strength between the period of May 2011 and February 2012. During this period, the SVE system had minimum effects on soil and groundwater concentrations. Consequently, the mass reduction required to reach dCULs was obtained based on average TCE concentrations in the Zone A source zone wells MW-52S and MW-53S (Environmental Partners, 2012, 2013). An average mass reduction needed to reach dCULs of **66%** was estimated.

	TCE Concentration (ug/L)	
Date	**MW-52S**	**MW-53S**
5/19/2011	12	9.2
6/15/2011	6.3	4.5
7/26/2011	2.1	3.9
8/25/2011	1.6	8.8
9/30/2011	2.5	7.5
10/24/2011	0.96	3.9
11/14/2011	1.3	2.8
12/19/2011	2.9	3.8
1/24/2012	6.6	9
2/27/2012	58	-
Average	**9.4**	**5.9**
dCUL	2.5	2.5
% Reduction	73%	58%
Average	66%	

B.3. Method 3: SVEET Model to Determine Percent Mass Reduction

SVEET Inputs and Site-Specific Parameters

Site characterization reports and SVE operation measurements were used to establish site-specific values for key restoration time frame model inputs. In addition, the author of the SVEET tool, Dr. Mike Truex of the Pacific Northwest National Lab (PNNL), was consulted to review application of the SVEET Tool to the Zone A SVE system. Of the 11 site-specific parameters, all but the following five were within the applicable input ranges of SVEET: Temperature, Source Width, Average Recharge, and Groundwater Velocity. As prescribed by the SVEET guidance manual (Truex et al., 2013) and after discussions with Dr. Truex, scaling factors were used to adjust the SVEET results to account for those five parameters.

The SVEET modeling has limitations, in that the tool finds the most similar modeling run from the suite of STOMP runs embedded in the tool. Additionally, the use of scaling factors increases the uncertainty in the model results to a small extent. Overall, these results are likely to be representative of actual conditions at Zone A, but may be lower resolution than a site-specific, detailed modeling analysis. Rebound tests are recommended when the system gets near the potential endpoints predicted by the SVEET tool, therefore, a safety factor was added to the Required % Reduction calculated in Table 3.1.

SVEET Input Data

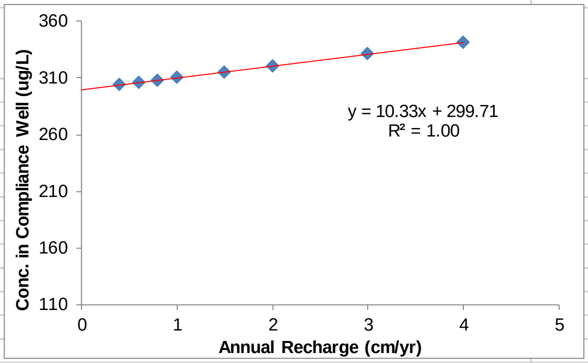
Parameter	Value	Units	Notes	Source
Temperature:	22	ºC	Groundwater temperatures from MW52S, MW53S	See tab "Temps"
Avg. Moisture Content:	7.2	wt%	Assume wt%. Mass of water per mass of dry soil in %.	Soil moisture data in a spreadsheet provided my Mike, Anchor QEA via email on 7/31/2013.
Avg. Recharge:	0.4	cm/yr	With cap, no recharge. Use lowest value allowable in model	
Vadose Zone Thickness:	23	m	All geology without cap, and engineered fill.	See tab "Geology,Thicknesses"
Depth to Top of Source:	3.4	m	Top of fill to top of stacked drums	See tab "Geology,Thicknesses"
Source Thickness:	5.2	m	Total thickness from bottom of stacked drums to bottom of Touchet beds	See tab "Geology,Thicknesses"
Source Width (= Length):	41	m	Calculated source area around VEW-7D only as VEW-6D had much lower TCE vapor concentrations and will clean up before VEW-6D	See tab "SourceArea"
GW Darcy Velocity:	0.3	m/day	Average seepage rate of 21 ft/day. Converted to Darcy velocity assuming porosity = 0.3; darcy velocity = 1.9 m/day. Since maximum of program is 0.3 ft/day, used scaling method prescribed by Dr. Mike Truex.	Anchor QEA, 2014. Draft Focused Feasibility Study Pasco Landfill National Priorities List Site. September 2014.
Distance to Compliance Well:	50.0	m	Center of source area in plan view to NVM-01 or MW-47S was 59 m. Selected program option of 50 m.	See tab "SourceArea"
Compl. Well Screen Length:	5.0	m	Assume average screen interval of existing monitoring wells: MW-50S, MW-52S, MW-53S. Average screen interval = 15 ft (4.6 m). Selected program minimum of 5 m.	See tab "ScreenInterval"
Source Gas Concentration:	5153	ug/L	Average of historical VEW-7I data (last year of data)	See tab "VEW-06I" and "VEW-07I"
Source Gas Concentration:	959	[ppmv]	Above converted to ppmv using MW of TCE	

SVEET Scaling Factors

ANNUAL RECHARGE

All input parameters kept same except Annual Recharge

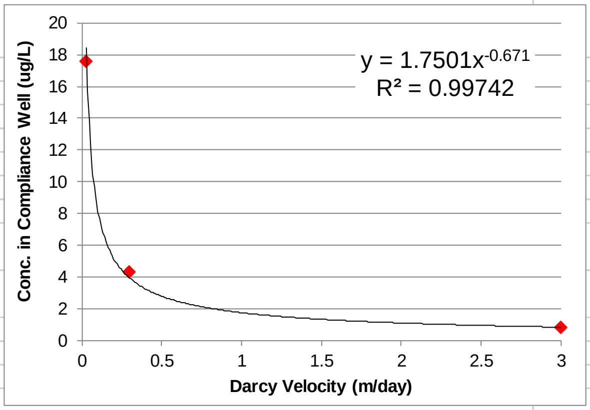
	Conc. in Compliance Well (ug/L)
0	299.7
0.4	304
0.6	306
0.8	308
1	310
1.5	315
2	320
3	331
4	341
Scaling Factor	**0.99**



GROUNDWATER DARCY VELOCITY

General Extrapolation: Use Columns C2 (ppb) and q (m/d) from Table 2 (Truex et al., 2009)

Darcy Velocity (m/day)	**Conc. in Compliance Well (ug/L)**	
0.03	17.6	
0.3	4.3	(Max. allowable in SVEET)
3	0.8	
Exponent	-0.671	
Constant	1.7501	
Site-Specific Darcy Velocity	1.9	m/day
Site-Specific Conc. In Compliance Well	1.1	ug/L
Scaling Factor	**0.26**	



SCALING FACTORS

Annual Recharge	**0.99**
Groundwater Velocity	**0.26**
Overall Scaling Factor	0.26
SVEET Overprediction Factor	3.8

SVEET RESULTS

Base Run:

2016 Soil Vapor Conc.	959	ppmv
2016 Soil Vapor Conc.	5153	ug/L vapor
SVEET Predicted 2016 TCE GW Conc.	**304**	ug/L TCE in groundwater

But SVEET Overpredicts Groundwater Concentrations by a factor of 3.8

SVEET Overprediction Factor	**3.8**	
SVEET Corrected 2016 TCE GW Conc.	79	ug/L TCE in groundwater
Draft Clean Up Level (dCUL)	2.5	ug/L
% reduction need to meet dCUL	**96.8%**	**%**
2016 Soil Vapor Conc.	**5153**	ug/L
Target Soil Vapor Concentration	**162**	ug/L
2016 Soil Vapor Conc.	**959**	ppmv
Target Soil Vapor Concentration	**30**	ppmv

APPENDIX C. METHOD 1: BOX MODEL METHOD BACKGROUND INFORMATION

C.1 Monte Carlo Methodology

Because of the uncertainty and range in input data, a statistical approach called Monte Carlo analysis was used with the Box Model to estimate the statistics and probability of different restoration time frames. For example, a Monte Carlo analysis provides results such as:

- the most likely (50th percentile) restoration time frame;
- the value where there is a 90 percent chance that the actual restoration time frame is equal to or less than that value (90th percentile); and
- the entire statistical distribution of restoration time frames.

What is Monte Carlo Analysis?

Monte Carlo analysis is a method of analyzing and quantifying uncertainties in model outputs due to the uncertainties in the input parameters (Rong et al., 1998). It refers to a computer based system that uses random numbers with a probability distribution between a specified range to obtain an approximation for the parameter of interest (USEPA, 1997; Bergin and Milford, 2000). This technique allows for the use of ranges of input data rather than relying on a single value.

Where Can Monte Carlo Analysis Be Applied?

In physics-related problems, Monte Carlo methods are quite useful for simulating systems with many coupled degrees of freedom, such as fluids. Other examples include modeling phenomena with significant uncertainty in inputs, such as the calculation of risk in business. In application to space and oil exploration problems, Monte Carlo–based predictions of failure, cost overruns and schedule overruns are routinely better than human intuition or alternative "soft" methods. In 1997, the USEPA published the “Guiding Principles for Monte Carlo Analysis” for environmental applications, stating:

> *“Such probabilistic analysis techniques as Monte Carlo analysis, given adequate supporting data and credible assumptions, can be viable statistical tools for analyzing variability and uncertainty in risk assessments.”*

How Does Monte Carlo Analysis Work?

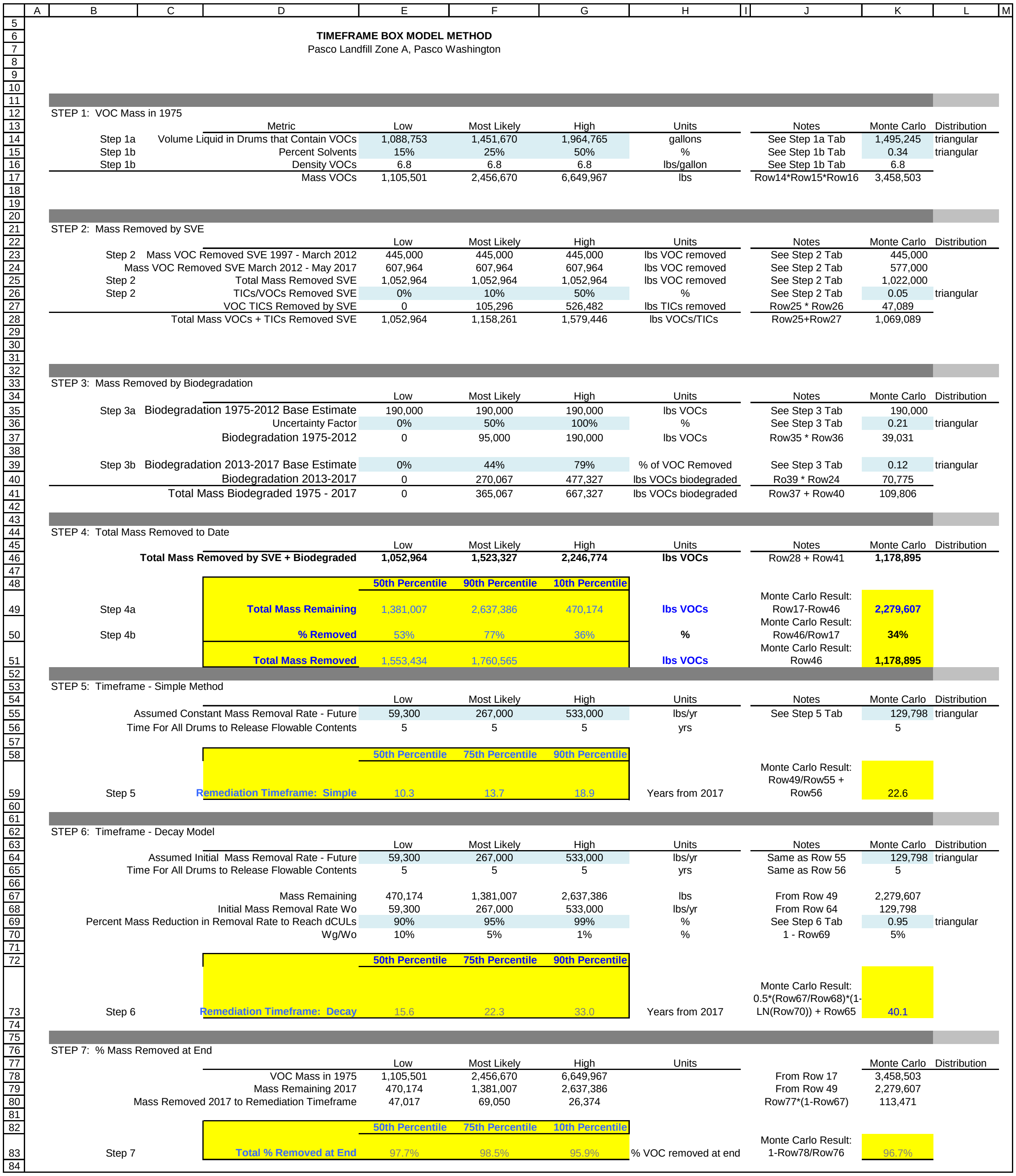
In the Monte Carlo approach, an input parameter is defined based on the underlying statistical distribution rather than a single value. A random number is then selected from the defined distribution and assigned as the value of the parameter and a result calculated. The selection of random numbers is repeated a large number of times (typically 100 to 1000) yielding an equivalent number of results. This group of results is then used to explain the likelihood, or the probability, of reaching various answers.

As an example, consider a pair of dice (each with a face value ranging from one to six). We would like to know the probability of rolling a particular sum of the dice. There are 36 possible outcomes for a pair of dice. Each of the sums can be placed in one of 11 “bins”. A probability for rolling a particular sum can then be calculated. For example, there is a 17 percent probability of rolling a “7”.

Another way of estimating the probablity of rolling the dice is to actually roll the dice a large number of times, say a 100 times. For each roll, the sum is recorded as a hit in one of the same 11 “bins” as above. After the 100th throw, the “hits” in the bins are tallied. For example, if 10 throws out of 100 gave a sum of 8, then the probablity of rolling an 8 is 10/100 or 10 percent. Obviously, the accuracy of this method depends of the number of times the dice are rolled. The larger the number of throws the more accurate the result.

Instead of manually rolling the dice, however, a Monte Carlo simulation can be used to easily reproduce the results. Because we know that each dice can range from 1 to 6, and each face has an equal probabilty of being rolled, we can use a uniform distribution. Running 10,000 simulations yields a 18 percent probability of rolling a “7”.

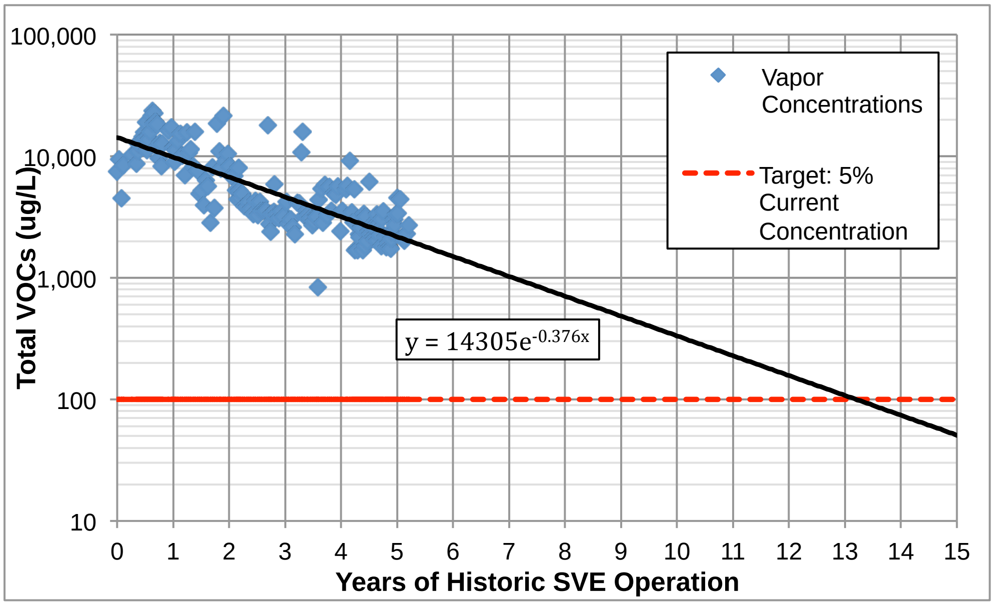
C.2 Monte Carlo Input Spreadsheet

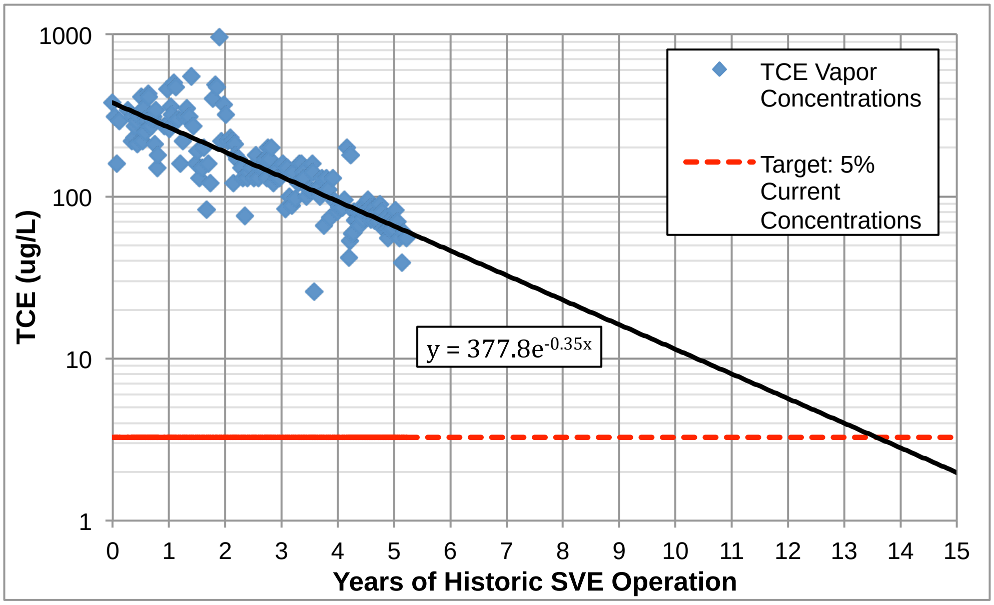


	A	B	C	D	E	F	G	H	I	J	K	L	M
5													
6					**TIMEFRAME BOX MODEL METHOD**								
7					Pasco Landfill Zone A, Pasco Washington								
8													
9													
10													
11													
12		STEP 1: VOC Mass in 1975											
13				Metric	Low	Most Likely	High	Units		Notes	Monte Carlo	Distribution	
14		Step 1a		Volume Liquid in Drums that Contain VOCs	1,088,753	1,451,670	1,964,765	gallons		See Step 1a Tab	1,495,245	triangular	
15		Step 1b		Percent Solvents	15%	25%	50%	%		See Step 1b Tab	0.34	triangular	
16		Step 1b		Density VOCs	6.8	6.8	6.8	lbs/gallon		See Step 1b Tab	6.8		
17				Mass VOCs	1,105,501	2,456,670	6,649,967	lbs		Row14*Row15*Row16	3,458,503		
18													
19													
20													
21		STEP 2: Mass Removed by SVE											
22					Low	Most Likely	High	Units		Notes	Monte Carlo	Distribution	
23		Step 2		Mass VOC Removed SVE 1997 - March 2012	445,000	445,000	445,000	lbs VOC removed		See Step 2 Tab	445,000		
24				Mass VOC Removed SVE March 2012 - May 2017	607,964	607,964	607,964	lbs VOC removed		See Step 2 Tab	577,000		
25		Step 2		Total Mass Removed SVE	1,052,964	1,052,964	1,052,964	lbs VOC removed		See Step 2 Tab	1,022,000		
26		Step 2		TICs/VOCs Removed SVE	0%	10%	50%	%		See Step 2 Tab	0.05	triangular	
27				VOC TICS Removed by SVE	0	105,296	526,482	lbs TICs removed		Row25 * Row26	47,089		
28				Total Mass VOCs + TICs Removed SVE	1,052,964	1,158,261	1,579,446	lbs VOCs/TICs		Row25+Row27	1,069,089		
29													
30													
31													
32													
33		STEP 3: Mass Removed by Biodegradation											
34					Low	Most Likely	High	Units		Notes	Monte Carlo	Distribution	
35		Step 3a		Biodegradation 1975-2012 Base Estimate	190,000	190,000	190,000	lbs VOCs		See Step 3 Tab	190,000		
36				Uncertainty Factor	0%	50%	100%	%		See Step 3 Tab	0.21	triangular	
37				Biodegradation 1975-2012	0	95,000	190,000	lbs VOCs		Row35 * Row36	39,031		
38													
39		Step 3b		Biodegradation 2013-2017 Base Estimate	0%	44%	79%	% of VOC Removed		See Step 3 Tab	0.12	triangular	
40				Biodegradation 2013-2017	0	270,067	477,327	lbs VOCs biodegraded		Ro39 * Row24	70,775		
41				Total Mass Biodegraded 1975 - 2017	0	365,067	667,327	lbs VOCs biodegraded		Row37 + Row40	109,806		
42													
43													
44		STEP 4: Total Mass Removed to Date											
45					Low	Most Likely	High	Units		Notes	Monte Carlo	Distribution	
46				**Total Mass Removed by SVE + Biodegraded**	**1,052,964**	**1,523,327**	**2,246,774**	**lbs VOCs**		Row28 + Row41	**1,178,895**		
47													
48					**50th Percentile**	**90th Percentile**	**10th Percentile**						
49		Step 4a		**Total Mass Remaining**	1,381,007	2,637,386	470,174	**lbs VOCs**		Monte Carlo Result: Row17-Row46	**2,279,607**		
50		Step 4b		**% Removed**	53%	77%	36%	**%**		Monte Carlo Result: Row46/Row17	**34%**		
51				**Total Mass Removed**	1,553,434	1,760,565		**lbs VOCs**		Monte Carlo Result: Row46	**1,178,895**		
52													
53		STEP 5: Timeframe - Simple Method											
54					Low	Most Likely	High	Units		Notes	Monte Carlo	Distribution	
55				Assumed Constant Mass Removal Rate - Future	59,300	267,000	533,000	lbs/yr		See Step 5 Tab	129,798	triangular	
56				Time For All Drums to Release Flowable Contents	5	5	5	yrs			5		
57													
58					**50th Percentile**	**75th Percentile**	**90th Percentile**						
59		Step 5		**Remediation Timeframe: Simple**	10.3	13.7	18.9	Years from 2017		Monte Carlo Result: Row49/Row55 + Row56	22.6		
60													
61													
62		STEP 6: Timeframe - Decay Model											
63					Low	Most Likely	High	Units		Notes	Monte Carlo	Distribution	
64				Assumed Initial Mass Removal Rate - Future	59,300	267,000	533,000	lbs/yr		Same as Row 55	129,798	triangular	
65				Time For All Drums to Release Flowable Contents	5	5	5	yrs		Same as Row 56	5		
66													
67				Mass Remaining	470,174	1,381,007	2,637,386	lbs		From Row 49	2,279,607		
68				Initial Mass Removal Rate Wo	59,300	267,000	533,000	lbs/yr		From Row 64	129,798		
69				Percent Mass Reduction in Removal Rate to Reach dCULs	90%	95%	99%	%		See Step 6 Tab	0.95	triangular	
70				Wg/Wo	10%	5%	1%	%		1 - Row69	5%		
71													
72					**50th Percentile**	**75th Percentile**	**90th Percentile**						
73		Step 6		**Remediation Timeframe: Decay**	15.6	22.3	33.0	Years from 2017		Monte Carlo Result: 0.5*(Row67/Row68)*(1-LN(Row70)) + Row65	40.1		
74													
75													
76		STEP 7: % Mass Removed at End											
77					Low	Most Likely	High	Units			Monte Carlo	Distribution	
78				VOC Mass in 1975	1,105,501	2,456,670	6,649,967			From Row 17	3,458,503		
79				Mass Remaining 2017	470,174	1,381,007	2,637,386			From Row 49	2,279,607		
80				Mass Removed 2017 to Remediation Timeframe	47,017	69,050	26,374			Row77*(1-Row67)	113,471		
81													
82					**50th Percentile**	**75th Percentile**	**10th Percentile**						
83		Step 7		**Total % Removed at End**	97.7%	98.5%	95.9%	% VOC removed at end		Monte Carlo Result: 1-Row78/Row76	96.7%		
84													

C.3 Use of TCE as a Proxy for VOC Reduction

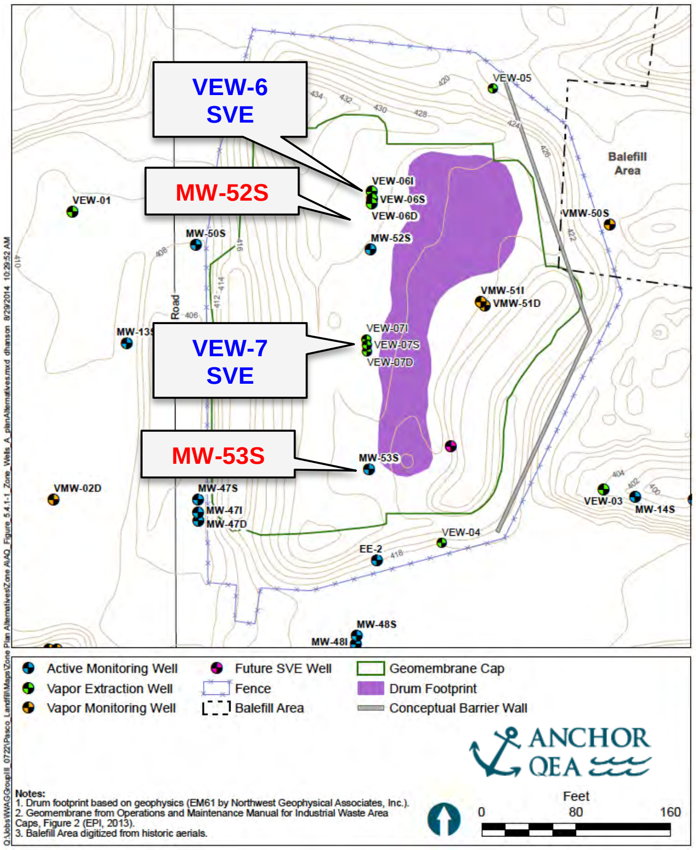
As shown in the figures below, during the period 2012 to 2014, the trendline for total VOC concentrations in the SVE effluent has been similar to the trendline for TCE in the SVE effluent, supporting the use of the TCE analysis as a proxy for the VOC reduction requirements.





APPENDIX D. WHAT CAUSES INCREASES IN GROUNDWATER TCE CONCENTRATION?

TCE concentrations in well MW-52S (located in line between SVE well locations VEW-6 and VEW-7 and about 45 feet south of VEW-6; see Figure D.1) were above dCULs prior to March 2012 when the enhanced SVE system began operations. Soon afterward, concentrations dropped to below the detection limit (non-detect) or very low levels as shown in Figure D.2 (top panel). However, in early 2014 concentrations increased by several orders of magnitude.



Notes:
1. Drum footprint based on geophysics (EM61 by Northwest Geophysical Associates, Inc.).
2. Geomembrane from Operations and Maintenance Manual for Industrial Waste Area Caps, Figure 2 (EPI, 2013).
3. Balefill Area digitized from historic aerials.

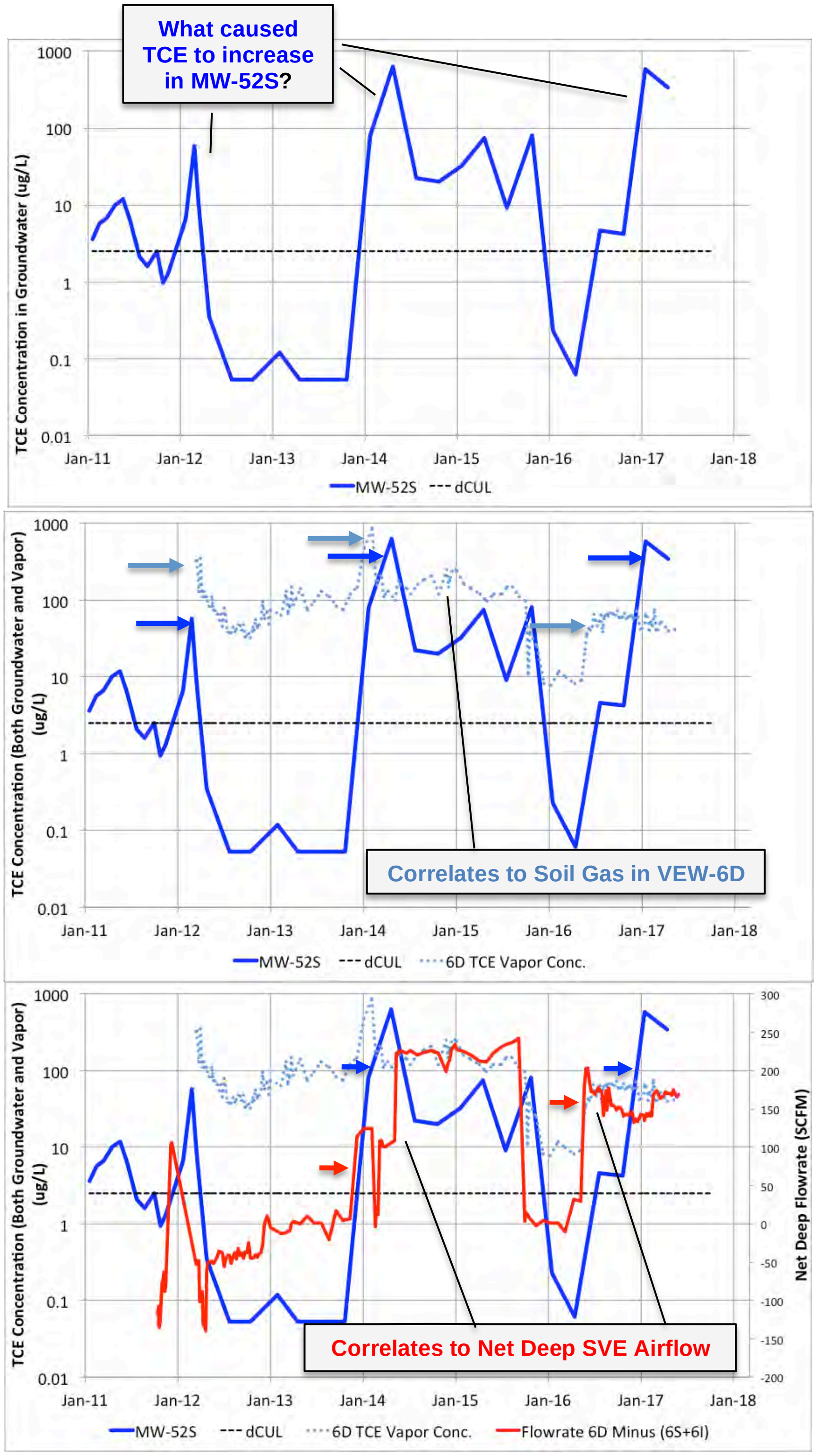
Figure D-1. *Location of SVE wells and groundwater monitoring wells MW-53S and MW-52S.*

It was hypothesized that the 2014-2015 TCE increases and increases in early 2017 were caused by **changes in the Zone A airflow patterns induced by the SVE system.** That is, reductions in extraction from the shallow and intermediate wells and increases in extraction from the deep wells drew TCE vapors deeper into the cooler subsurface where it condensed. As shown in Figure D.3, the shallow SVE wells have screens that extend to 11-15 feet below ground surface; the intermediate SVE wells to about 36 feet and the deep wells to about 65 feet below ground surface.

To test this hypothesis, first, the TCE vapor concentrations in SVE well VEW-6D were plotted and compared to the TCE concentrations in groundwater (middle panel, Figure D.2). As can be seen, changes in TCE soil gas concentrations are correlated to changes in TCE concentrations in groundwater in MW-52S.

Finally, the "Net Deep Flowrate" (i.e., flowrate at well VEW-6D minus the flowrate of VEW6S+VEW-6I) at SVE location 6 was plotted vs. time (red line, bottom panel, Figure D.2). If extraction rates at VEW-6D exceed the extraction rates at VEW-6I and VEW-6S, then the mass transfer from Zone A vadose zone to groundwater will increase and draw soil gas with higher concentrations of TCE closer to groundwater. As can be seen, both the TCE soil gas and TCE groundwater concentrations are strongly correlated to the Net Deep Flowrate, with about a one-month lag. This correlation, including the 30-day lag, is shown by the linear relationship between Net Deep Airflow and the TCE concentration in groundwater (Figure D.3).

A much weaker correlation was observed at groundwater monitoring well MW-53S, located south of SVE Location 7. This is likely because MW-52S is located in the middle of the Zone A source zone while MW-53S is located at the very far southern end of the drum footprint area (Figure D.1). Therefore, any deep airflow caused by VEW-7D would tend to clean the air past MW-53, reducing the soil gas concentrations.



What caused TCE to increase in MW-52S?

Correlates to Soil Gas in VEW-6D

Correlates to Net Deep SVE Airflow

Figure D-2. *Top: TCE concentration in groundwater at monitoring well MW-52S from January 2011 to May 2017. Note log-scale. Middle: TCE in groundwater shows a correlation to soil vapor concentration in VEW-6D and (Bottom Panel) to the net deep airflow (Vapor flowrate at VEW-6D minus flowrate at VEW-6S+VEW6I. Note the blue line appears to lag the red line by about a month.*

A similar correlation can also be observed with naphthalene concentrations in groundwater, as shown in Figure D.4. This suggests a potential condensation mechanism delivers the contaminants to groundwater when there is net deep vapor flow and not a diffusion-only scenario.

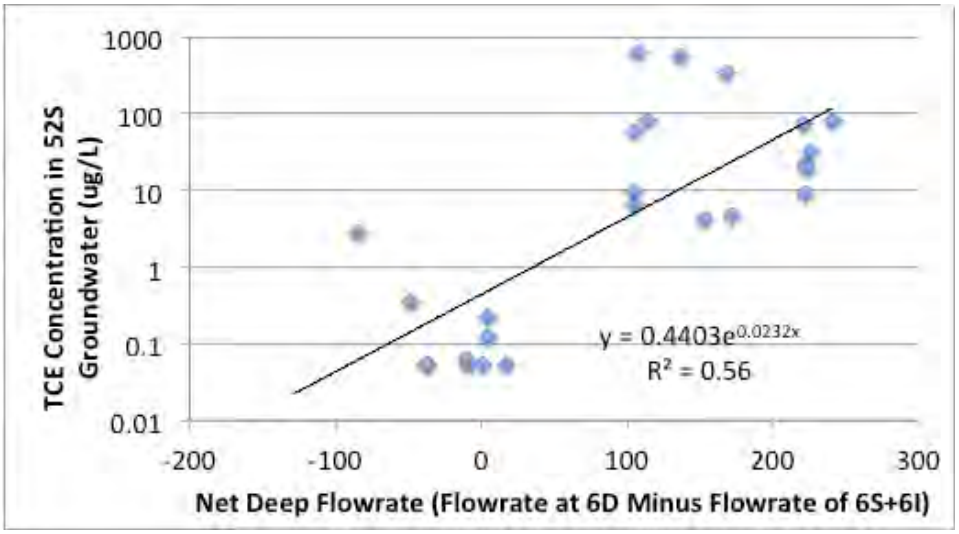


Figure D-3. *Correlation between Net Deep Flowrate and the TCE concentration in groundwater at MW-52S from the closest nearby monitoring period. Note a 30-day lag period was built into the correlation.*

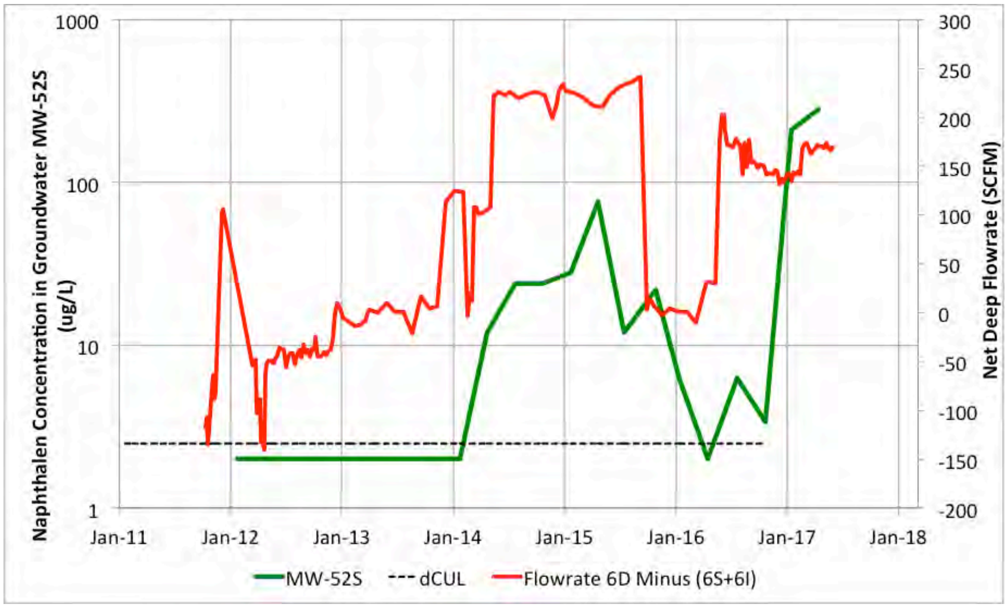


Figure D-4. *Top: Naphthalene concentration in groundwater at monitoring well MW-52S from January 2011 to May 2017 (green line). Note log-scale on left hand y-axis. Net deep airflow (vapor flowrate at VEW-6D minus flowrate at VEW-6S+VEW6I (red line).*

Key Points

- The TCE groundwater concentration “spikes” in 2013-2017 was likely caused by an increase in the Net Deep Flowrate where higher extraction rates at VEW-6D exceeded the extraction rates at VEW-6I and VEW-6S.
- This drew soil gas with higher concentrations of TCE closer to groundwater, thereby increasing the mass transfer from Zone A vadose zone to groundwater.
- A similar pattern was observed with naphthalene, a semi-volatile compound with enough volatility to be influenced by SVE systems.
- No other mechanism, such as breaking drums and subsequent non-aqueous phase liquids (NAPL) transport to groundwater, is required to explain the higher TCE concentrations at well MW-52S in 2013-2017.

APPENDIX K
ZONE A HEATING EVALUATION MEMORANDUM
PASCO LANDFILL NPL SITE

Prepared for
Industrial Waste Area Generator Group III

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MEMORANDUM

To:	Charles Gruenenfelder, Washington Department of Ecology	**Date:**	October 29, 2012
From:	Bob Isenberg, P.E., CPG, and John Richards, P.E., SCS Engineers Jessica Goin, Ph.D., and Dimitri Vlassopoulos, Ph.D., Anchor QEA Thom Morin, L.G., Environmental Partners	**Project:**	
Re:	Zone A Heating Evaluation, Pasco Sanitary Landfill Site		

INTRODUCTION

The following technical memorandum documents activities the Industrial Waste Area Generator Group III (IWAG) conducted to establish whether or not the conditions in Zone A of the Pasco Sanitary Landfill (PSL) Site are indicative of subsurface combustion or subsurface heating not associated with combustion (i.e., degradation of solid or industrial waste). The activities were proposed by the IWAG in the *Outline of Proposed Activities – Zone A Heating Evaluation* (SCS Outline of Proposed Activities; SCS 2012), which was accepted by the Washington Department of (Ecology) on June 18, 2012.

BACKGROUND

The upgraded soil vapor extraction (SVE) system operating at Zone A underwent a period of extended startup and operational testing. This testing included four 2-week tests under various flow rates and vacuums for the shallow-, intermediate-, and deep-zone SVE wells. During Test No. 2 and Test No. 4, which included extraction from the intermediate-depth wells, a trend of increasing temperatures was observed in the effluent gas from well VEW-06I. The temperature of extracted off-gas in this well increased over the course of Test No. 2 and Test No. 4 from approximately 100 degrees Fahrenheit (100°F) to as much as 121°F. Based on that observation, Test No. 4 was extended for 2 additional weeks, during which the VEW-06I vapor temperature increased to a high of 123°F on May 15, 2012. During this 2-week extension of Test No. 4, the IWAG also agreed to collect carbon monoxide (CO) readings using a field instrument. The field CO readings ranged from 0 ppm to 730 ppm.

Although the highest CO value is elevated, field instruments are known to give high CO readings (FEMA 2002) and it was recorded at VEW-07I, which did not have elevated temperatures. The increase in off-gas temperature at VEW-06I and the CO levels at VEW-06I and VEW-07I were discussed with Ecology, which expressed concern that the rise in temperatures and CO levels were potentially indicative of subsurface combustion. Based on that concern, Test No. 4 was terminated on May 16 and follow-on Test No. 5 was initiated. Test No. 5 used only minimal extraction flow rates of approximately 5 standard cubic feet per minute (scfm) from VEW-06I and VEW-07I and these test conditions were maintained through a 4-week evaluation period as specified in the Outline of Proposed Activities. The SVE system is currently operating in the Test No. 5 flow configuration.

INDICATORS OF SUBSURFACE HEATING EVENTS

According to the Federal Emergency Management Agency (FEMA 2002) and Ohio Environmental Protection Agency (OhioEPA 2011), there are six key indicators of a heating event related to subsurface combustion in landfills. Given that Zone A is an industrial waste landfill, these indicators are considered useful for this evaluation. In approximate order, from the most readily visible/easily discernible (which is physical settlement) to indicators requiring invasive measurements or testing, these are:

1. Substantial settlement in a short period of time
2. Smoke or smoldering odor from the facility or subsurface probes
3. Elevated CO levels in excess of 500 to 1,000 parts per million – Volume (ppmV)
4. Combustion residue in probes or wells
5. Increases in gas temperature above 140°F
6. Subsurface soil temperatures of greater than 170°F[1]

These indicators are widely accepted as indicators of subsurface heating events related to combustion. Indicators, such as settlement, smoke, CO, combustion residues, and subsurface soil and gas temperatures are equally applicable to municipal solid waste (MSW) landfills, construction and demolition debris (C&D) landfills, and industrial waste landfills.

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[1] Subsurface soil temperatures up to 170°F are consistent with bacterial activity (Henderson and Sperling 2001).

There are also a number of geochemical indicators that can be applied to analysis of extracted gases to distinguish between combustion-related heat and heat generated by normal biodegradation of solid waste. Among these are:

- Nitrogen oxide (NO), nitrogen dioxide (NO_2), and nitrous oxide (N_2O) concentrations
- Reduced nitrogen compounds (ammonia [NH_3] and hydrogen cyanide [HCN])
- Stable isotope analysis of CO in landfill gas
- Stable isotope analysis of methane (CH_4) and carbon dioxide (CO_2) in landfill gas

Data and visual observations related to the six key combustion indicators and the geochemical indicators were collected for the Zone A heating evaluation. The data from this evaluation were periodically provided to Ecology throughout the 4-week evaluation period and a compilation of the data was provided to Ecology on July 27, 2012. Interpretations of the data with respect to subsurface combustion were presented to Ecology in a meeting on August 4, 2012. This technical memorandum provides further documentation of the Zone A heating evaluation.

DATA COLLECTION

The 4-week evaluation period began on June 18, 2012 and continued through July 13, 2012. However, temperature, CO, CO_2, oxygen (O_2), and CH_4 data collection began in early May. Initially, CO and CH_4 data were collected by field instruments, but starting on May 14, 2012, CO and CH_4 samples were collected in the field and sent to analytical laboratories to address concerns about the accuracy of field instruments especially with respect to CO (FEMA 2002). Temperature, CO, CO_2, O_2, and CH_4 data collected before the 4-week evaluation period began have been included in the Zone A heating evaluation. Data collected as part of this evaluation are tabulated in Attachment D.

Chemical and Temperature Data

Tasks 3, 4, 6, and 7 in the SCS Outline of Proposed Activities included measurement, sampling, and analysis of the extracted gases from the SVE wells. These measurements and analyses were components of Key Indicators No. 3 and No. 5. Chemical analyses of major and trace constituents of extracted gases also provide information on the potential source of the heating beneath Zone A, other than combustion or pyrolosis.

The proposed measurement and sampling parameters and the schedule for those activities were discussed in the SCS Outline of Proposed Activities. The schedule and proposed activities were modified as necessary based on field-specific considerations and personnel availability.

Any modifications to the schedule and parameters provided in the SCS Outline of Proposed Activities were proposed to, and approved by, Ecology before implementation.

Field Data

Table 1 presents the field sampling schedule that was implemented during the Zone A heating evaluation. Figure 1 indicates the sampling locations.

Table 2 presents a summary of the field instruments used for collection of field parameters. Each instrument was calibrated and operated according to the manufacturers' specifications and requirements.

Laboratory Data

Table 3 presents a summary of conventional laboratory analyses used for chemical analytes.

Because of a repeated lack of detections, laboratory analysis of NH_3 and HCN were removed from the sampling program after June 25, 2012, with Ecology approval.

Table 4 presents a summary of laboratories and methods used for isotopic analyses. Isotopic analyses of CH_4 at VEW-06I and VEW-07I for samples collected on July 9, 2012, were conducted at the SoMAS Laboratory at Stony Brook University instead of Isotech Laboratories due to the low levels of CH_4 detected at these wells (data pending).

Temperature Profiles

Task 4 (Temperature Measurements) specified in the SCS Outline of Proposed Activities consisted of subsurface soil temperature measurements to assess Key Indicator No. 6 at Zone A wells. Soil temperature was assessed by downhole measurement of the temperature of the steel well casings at MW-52S, MW-53S, VEW-06D, VEW-07D, and VMW-51D and of the PVC well casings at VEW-04 and VEW-05,.

Vertical temperature profiles were performed by Rowland French of Zonge International (ZI). The measurements were observed by John Richards (SCS Engineers) and additional field technical support was provided by Eric Jensen (Environmental Partners).

Measurements were performed using direct reading thermocouples on a downwell probe. The probe was equipped with two thermocouples to provide data redundancy. A description of the probe is provided in the ZI report presented in Attachment A. Temperature measurements were recorded every 2.5 feet vertically within the well down to the depth of the top of the screened interval. Well casing temperature measurements are not possible within the screened interval due to the smaller inside diameter of the wire-wound screens.

Aerial Thermal Imaging

Aerial thermal imaging can be useful in showing locations of surface heating that may indicate subsurface hot spots. This condition occurs when the degree of subsurface heating is sufficient to affect surface temperatures above the general area of the heating event. In the present case, the aerial thermal imaging was implemented as a tool to support location of additional settlement plates in Zone A to assess Key Indicator No. 1.

The aerial thermal imaging was conducted by Stockton Infrared Thermographic Services (Stockton) on June 27, 2012. The report provided by Stockton is presented in Attachment B.

Visual Observations

Settlement

On July 11, 2012, John Richards from SCS Engineers, accompanied by Chuck Gruenenfelder and Jeremy Schmidt of Ecology, inspected the Zone A cap to observe surficial conditions for the purpose of identifying areas of potential settlement and potential locations for additional settlement monitoring plates. During the visit, SCS identified one area that exhibited potential surface cracking that could be related to either tension or soil desiccation, as well as areas that appeared depressed below the surrounding ground level. These areas were identified on a map and the locations of additional settlement monitoring plates on Zone A are based primarily on the results of this inspection.

After reviewing and evaluating the heating evaluation data, Mr. Richards performed a subsequent inspection of the Balefill Area on September 5, 2012, to assess surface conditions and potential placement of settlement monitoring plates in that area. During his visit, Mr. Richards identified areas where baled waste was exposed and he also measured soil cover thickness at four locations where the baled waste had a soil cover. Typical cover thickness was at least 18 to 24 inches in the locations tested within the Balefill Area. At one location, Mr. Jensen and Mr. Richards were unable to advance the depth of the hole deeper than 18 inches.

Wells and Piping

During the vertical temperature profiling discussed above, the condition of the wells was visually observed for evidence of a combustion event. These observations were performed by Mr. Richards when the wells were disassembled for insertion of the temperature probe. The inspection included visual inspection of the downhole casing, as well as the elbows connected to the vapor extraction system. The inside of the above-ground elbows connected to VEW-05, VEW-04, VEW-06D, and VEW-07D were visually inspected and also wiped with a white cotton glove to examine for an accumulation of soot and crystalline deposits that may be an indication of combustion. However, what was observed was biological growth and some minor scale deposits. The other wells in which the temperature profiling was performed (MW-52S, MW-53S, and VMW-51D) did not have elbow connections to examine.

Findings

Aerial Thermal Imaging

Analysis of the thermal imaging showed several areas with slightly elevated temperature. All of the anomalous areas were outside Zone A. Field inspection of these areas showed that the anomalies were likely due to construction debris or a surface soil type that acts as daytime heat sink (i.e., not a reflection of subsurface temperature).

The surface area of Zone A showed little temperature contrast with the exception of the SVE wells and piping. Consequently, the thermal imaging did not provide information useful for locating settlement plates; instead, proposed settlement plate locations are based on visual observations.

Settlement

During the July 10, 2012, site inspection, Mr. Gruenenfelder, Mr. Schmidt, and Mr. Richards inspected the Zone A cover. The areas where the cover appears to exhibit a potential for increased settlement, new or previously unobserved settlement, and surficial cracking were discussed.

Three potential areas of settlement were identified on the western slope of Zone A. Two of the three areas are located near the southwest corner of the site. One of those two areas had previously been monitored (SB-9 and SB-10), but it appeared that settlement may be progressing at a different rate than the surrounding area. The second area on the southwest slope, near the previously decommissioned well EE-3, had not been previously identified and is located west of SP-1 and the original settlement areas identified in 2008.

Additional areas of potential settlement were identified on the surficial soils of the Zone A cap. One area of soil exhibiting tension cracking is located about 35 feet south of settlement plate SP-3 and is about 90 feet long and 30 feet to 35 feet wide. The apparent southern extent of the cracking is west of the VEW-07S/I/D extraction wells. The cracking is arcuate in shape, discontinuous, and begins and ends near the top of the western slope at the slope break. The long axis of the cracking is roughly parallel to the top of the western slope of Zone A. The cracks in the soil range in width from about 5 mm (approximately 0.2 inches) to about 1 mm (approximately 0.04 inches). The depth to which a "pin flag" (approximately 0.1 inches in diameter) can be advanced into the cracks ranges between zero and approximately 12 inches. There was no measurable vertical offset of the cracking at the time of observation. Although this area was not included in the cover maintenance conducted in August 2011, some of the equipment used in conjunction with the maintenance was parked and traveled back and forth over this area. It is not discernible if the soil cracking in this area is due to the maintenance activities or other processes.

A relatively small depression has developed immediately north and east of settlement plate SP-2. This area is oval in shape, about 10 feet long (parallel to the top of the western slope), about 5 to 6 feet wide in the middle, about 6 inches or less in depth, and surrounded by surficial soil cracking. There is a vertical offset of about 1 inch at various locations in the cracking. On the east side of this depression, the vertical offset in the soil cracks appear to overlap from east to west. This was evident by grass being pushed over toward the west. The horizontal offset is less than 0.5 inch.

An area of potential settlement is located east of the SVE conveyance piping. This area is about 75 feet long and about 20 feet wide, trending north and south. It is located approximately 30 feet east of MW-53S and the buried SVE system conveyance piping. Due to the proximity to the buried piping, the occurrence of this slightly depressed area may be the result of construction activities during the installation of vapor extraction wells VEW-06 and VEW-07 and the associated conveyance piping.

The Ecology representatives identified an area of suspected settlement in the northeast portion of Zone A, roughly parallel to the surface water diversion on the perimeter of the cover. This area is roughly centered about 25 feet north of settlement marker SB-7 and would cover a relatively wide area (up to 60 feet west of the berm). Although near the berm, there is no evidence of erosion due to surface water flow in this area. Additionally, there was no observed cracking of the soils in this area.

The vegetation on the Surface of Zone A at the time of the visit was equally sparse, largely due to the time of year and the activities being conducted in the area. Due to the generally sparse nature, low rainfall, and high summertime temperatures, vegetation is not a good indicator of potential changes in the cover system at Zone A. However, due to the sparse vegetative cover, the observed cracking is visible and traceable, which facilitates settlement inspection.

There were no areas identified as having substantial settlement in a short period of time based on observations of previous settlement monitoring results and the site inspection. However, based on an understanding of overall site conditions and landfill settlement processes, it is recommended that additional settlement plates be installed within the limits of Zone A and outside of Zone A within the Balefill Area at the approximate locations shown on Figure 2. Actual locations will be selected in the field and the new settlement plates will be surveyed. Settlement plate monitoring shall be performed by a Washington-registered Professional Land Surveyor using the same datum as the current settlement plates.

Proposed settlement plate locations at Zone A were selected during the field visit on July 11, 2012, described above and coordinated with Ecology representatives during the field visit. Settlement plate locations in the Balefill Area were identified during a site visit on September 5, 2012. The surface of the balefill is relatively unremarkable and uniform, and does not exhibit obvious or visible indication of differential settlement. Therefore, locations of the settlement plates proposed in the Balefill Area were distributed so as to obtain settlement data that would provide useful comparisons to settlement within the adjacent (eastern) portion of Zone A where balefill waste was disposed, as well as in the area of the historic fire in the balefill that was successfully extinguished in the 1980s. Photographs of the proposed locations for settlement plates are provided in Attachment E.

Wells and Piping

The inside of the above-ground elbows connected to VEW-05, VEW-04, VEW-06D, and VEW-07D were visually inspected and wiped with a white cotton glove to examine for an accumulation of soot or crystalline deposits that may be an indication of combustion.. No soot or other foreign deposits were observed in the connecting elbows of these wells (Figure 3). Apparent biological growth was observed in VEW-05, VEW-04, and VEW-07D. VEW-06D did not have an accumulation of biological growth. Mr. Jensen stated that the biological growth was previously removed from VEW-05 monthly and less frequently from VEW-04 when those wells were under active SVE extraction. Initially, according to Mr. Jensen, biological growth in VEW-07I began to accumulate immediately after installation of that well. However, after one cleaning, and since active SVE extraction from that well, no additional biological growth has been observed. It is presumed that the biological growth accumulates in the elbows for two reasons: 1) the elbow is the first part of the extraction system that is exposed to atmospheric temperatures, and 2) the change in direction caused the velocity of the extracted vapors to be reduced. When extraction piping is exposed to the atmosphere, there is a general cooling, which causes water vapor to condensate on the surfaces, which may allow limited biological growth in those areas. The reduction in vapor velocity can also allow water vapor to condensate on the surfaces.

The observed piping conditions are not consistent with conditions that would indicate the occurrence of subsurface combustion or pyrolosis.

Temperature Profiles

As noted above, vertical temperature profiles were recorded in seven monitoring and vapor extraction wells completed through and around Zone A. The temperature profiles were intended to assess the lateral and vertical distribution of temperatures in subsurface soils and whether those temperatures exceed 170°F.

Figures 4 and 5 present the vertical temperature profiles on a north-south and east-west cross-section through Zone A. Temperatures are provided on a Fahrenheit temperature scale and overlain on the interpretive cross-section of soil conditions beneath Zone A that have previously been provided to Ecology.

Figure 6 provides a plan view of the vertical temperature profiles indicating the extent of the Zone A cap, the interpreted extent of Zone A wastes based on the geophysical survey, and the currently understood extent of balefill or other municipal waste beneath the Zone A cap.

The highest observed subsurface temperature was 148°F in well VMW-51D, with the next highest temperature of 131°F in well VEW-05. These wells are located on the eastern and northeastern portions of Zone A in areas that include substantial amounts of either baled municipal waste or other municipal waste debris. Subsurface temperatures decrease with distance away from the municipal waste area. Therefore, one source of the heat under Zone A is likely generated by the continued degradation of the municipal waste in the Balefill Area that is pulled into Zone A by the SVE system.

The vertical distribution of temperatures varies between the wells, but in general there is a clear vertical trend of lower surface temperatures, a zone of elevated temperature in the intermediate depth, and then decreasing temperatures at the deepest portion of the wells. The exceptions to this temperature trend are the two southernmost wells, VEW-04 and MW-53S, which are the most distant wells from the municipal waste area. No explanation is apparent for these exceptions.

The horizontal distribution of temperature varies with elevation in Zone A. Figures 7 and 8 were prepared to depict the temperature distributions at elevations 380 and 405 feet, respectively. These figures should be interpreted with caution as the temperature gradients are interpolations of limited measuring points and may not be fully indicative of temperature gradients. In addition, the temperatures shown may not be directly related as they are the result of different processes occurring in different areas of Zone A as discussed in the geochemical evaluation below.

The effect of subsurface temperatures on the integrity and lifespan of the Zone A HDPE/GCL liner was also evaluated. VEW-05 and MW-53I had the highest shallow subsurface temperatures of 119.6°F and 118.2°F, respectively. While this information suggests there are elevated temperatures in proximity to the HDPE/GCL liner in these locations, these temperature values are not unlike those encountered at the base of typical HDPE-lined sanitary landfills and are not unusually high or problematic. Research on HDPE liners does suggest that antioxidant depletion in HDPE geomembranes, which occurs in all landfill geomembranes as they age, may be accelerated by higher temperatures and potentially reducing the lifespan of HDPE. Since the near-membrane temperatures at Zone A are no greater than in any other landfill, this effect would not be any greater at Zone A than in any other landfill. Therefore, it remains our technical judgment that the physical and mechanical integrity of the cover system in Zone A, and its ability to protect the environment, is not compromised at the observed temperatures.

All of the observed subsurface temperature measurements within Zone A were more than 20°F below the 170°F threshold of Key Indicator No. 6 for a combustion-related heating event. Consequently, the subsurface temperature profiles do not suggest the presence of a combustion-related heating event beneath Zone A.

Geochemical Evaluation

The geochemical evaluation was performed to examine potential sources of elevated CO in VEW-06I and VEW-07I, and to determine if geochemical lines of evidence were consistent with the physical data supporting the absence of combustion. The geochemical evaluation included assessment of major and trace gas compositions, volatile organic compound (VOC) concentrations, and stable isotope analysis of CO and other gas components to distinguish between combustion versus bacterial or other processes. The geochemical evaluation focused on wells VEW-06I, VEW-07I, and VMW-51I, which are the wells with the highest temperature, CO, and CH_4, respectively.

Analysis of Gas and VOC Data

CO and Temperature

Field CO measurements up to 934 ppmV inVEW-07I and 517 ppmV in VEW-06I were recorded in May 2012 using a field instrument. As recommended, because of the inaccuracy of field CO measurements (e.g., FEMA 2002), samples were submitted for laboratory analysis. Laboratory CO values have ranged from 87 to 140 ppmV in VEW-06I and 140 to 440 ppmV in VEW-07I, but less than 70 ppmV in VMW-51I. Time series graphs of temperature, CO, and other gases at VEW-06I, VEW-07I, and VMW-51I are presented in Figures 9, 10, and 11, respectively.

Laboratory measurements of CO levels greater than 1,000 ppmV are considered indicative that subsurface combustion is occurring in a landfill, and levels between 100 and 1,000 ppmV are identified as "suspicious" and require further examination (FEMA 2002). Henderson and Sperling (2001) suggest that 100 to 500 ppmV CO indicates "potential smoldering nearby," and that a fire or exothermic reaction is "likely" with levels between 500 and 1,000 ppmV.

Vapor temperatures typically ranged from 120°F to 125°F in VEW-06I, 85°F to 97°F in VEW-07I, and 95°F to 100°F in VMW-51I[2]. FEMA (2002) identifies vapor temperatures in excess of 140°F as an indicator of subsurface combustion.

The relationship between temperature and CO is illustrated in Figure 12 for VEW-06I, VEW-07I, and VMW-51I. Concentrations of CO are greater in VEW-07I than in VEW-06I, while temperature is higher in VEW-06I than in VEW-07I. VMW-51I had a similar temperature range to VEW-07I, but the lowest CO of all three wells. The temperature and CO results are inconsistent with combustion as the source of elevated CO, as all three wells have temperatures well below 140°F, and the well with the highest temperatures has relatively low CO concentrations.

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[2] Lower temperatures were occasionally recorded at VEW-06I and VEW-07I before the 4-week evaluation period, but these were attributed to low purge rate and surface cooling from atmospheric conditions. More robust purging methods were implemented for the 4-week evaluation period, which resulted in more consistent temperatures during the evaluation period.

FEMA (2002) also identifies that subsurface temperature greater than 170°F is one of several possible indicators of subsurface combustion, not a sole indicator. Henderson and Sperling (2001) indicate that temperatures up to 170°F are consistent with bacterial activity, and not necessarily combustion-related. Maximum downhole temperatures at VEW-06D, VEW-07D, and VMW-51D were 117.0°F, 124.0°F, and 148.6°F, respectively. The maximum temperature in each is approximately located at the depth of the co-located intermediate wells. For downhole temperatures, the well with the highest temperature is adjacent to the intermediate well with the lowest CO.

CO Sources

Further analysis of the data and a review of pertinent literature were performed to examine potential sources of CO in VEW-06I and VEW-07I. In addition to incomplete combustion (smoldering), other sources of CO include anaerobic degradation of aromatic compounds (e.g., Harms et al. 1999), methanogenesis and methanotrophy (e.g., Haarstad et al. 2012; Zinder and Anguish 1992), degradation of ketones (e.g., Platen et al. 1990), and co-metabolic degradation of chlorinated solvents (e.g., Newman and Wackett 1997).

While an extensive list of VOCs was analyzed for VEW-06I and VEW-07I, a small subset of compounds consistently dominate the VOC composition (Figure 13). Aromatics (especially toluene), ketones, and chlorinated solvents account for 99% of the VOCs. Additionally, CH_4 is present, but concentrations are higher at VEW-06I than at VEW-07I (and highest at VMW-51I). As discussed below, there is evidence of methanogenesis in the Balefill Area and of CH_4 oxidation along the travel path from the Balefill Area to the Zone A extraction wells.

CO production, generated either by incomplete combustion or by bacterial degradation, is a byproduct of CO_2 production. O_2 and CO_2 concentrations measured in VEW-06I and VEW-07I over time define an approximately linear trend, with lower O_2 (and higher CO_2) samples generally occurring in VEW-06I (Figure 14). As shown in the figure, the slope of the line of the linear trend identifies the processes that generated the CO_2.

As indicated on Figure 14, the linear trend in the data is not consistent with combustion as the dominant source of CO_2. The slope defined by the data is intermediate between that expected for CH_4 oxidation and oxidation of VOCs such as toluene or 2-butanone, which indicates that CO_2 in these wells is mainly derived from oxidation of CH_4 and VOCs rather than landfill solid wastes or combustion processes.

CH_4 oxidation as a potential source of CO is supported by the relationship between VEW-06I and VEW-07I for O_2, CH_4, and CO. The O_2 and CO concentrations are greater in VEW-07I than in VEW-06I (Figure 15). In VEW-06I, O_2 concentrations are lesser and CH_4 concentrations are greater (Figure 16). These relationships are consistent with increased bacterial oxidation of CH_4 in VEW-07I with a corresponding increase in CO as a byproduct rather than incomplete combustion, which would be expected to produce more CO as O_2 is depleted.

The potential for a bacterial source of elevated CO concentrations is further supported by a review of relevant literature, which suggests that the concentrations of CO measured in VEW-06I and VEW-07I are consistent with bacterial degradation (Powell et al. 2006; Haarstad et al. 2012). For instance, Powell et al. found that CO concentration increased as CH_4/CO_2 decreased (Figure 17).

Trace Gases

Trace gases that are potential indicators of combustion (e.g., Nammari et al. 2004) were analyzed, including HCN, NH_3, NO, and NO_2. N_2O was measured as an indicator of bacterial activity. HCN was detected in only one sample out of seven sampling events at VEW-06I and VEW-07I, and that detection was within the range of the method reporting limit. NH_3 and NO were not detected. N_2O was detected at much greater concentrations than NO_2, consistent with bacterial activity. Based on the infrequent or lack of detection of HCN, NH_3, NO, and NO_2 and the frequent detection and relatively high concentration of N_2O, trace gases were not indicative of combustion.

Analysis of Isotopic Data

Compound-specific stable isotope analysis was performed on CO_2, CO, and CH_4 to supplement the interpretation of temperature, gas, and VOC data. Stable isotopes are widely used for evaluating the sources and formation pathways of gaseous components in the environment (Brenninkmeijer 2009; Stevens and Engelkemeir 1988; Stevens and Wagner 1989). In particular, they can be very useful in discriminating biodegradation from combustion processes, as these will affect the isotopic signatures in distinct but predictable ways (Wang et al. 2010; Saurer et al. 2009).

The stable isotope systematics of CH_4 and CO_2 in landfill gases have been studied extensively (Hackley et al. 1996; Kerfoot et al. 2003; Fritz et al. 1994). Stable carbon and hydrogen isotope ratios of CH_4 provide information on its origin (e.g., bacterial versus thermal). Stable C and O isotope ratios of CO_2 can identify combustion-derived CO_2 from other origins. Stable C and O isotope ratios of CO produced from different source materials (e.g., CH_4 or plant matter) by different processes (e.g., combustion or chemical oxidation) have been studied in the laboratory and have been widely used to determine sources contributing to CO in the atmosphere (Brenninkmeijer 1999; Conny 1998; Brenninkmeijer 2009; Kato et al. 1999).

Stable isotope data are reported as the abundance ratio of the trace isotope to the more abundant light isotope relative to the same ratio in an international reference standard (USEPA 2008; ITRC 2012). The ratio of the heavy and light isotope in the sample, relative to the ratio of the heavy and light isotope in the standard, is reported as the delta (δ) of the isotope in parts per mil ($^0/_{00}$). The two laboratories performing isotopic analysis both reported $\delta^{13}C$ relative to the Vienna PeeDee Belemnite (VPDB) standard. The SoMAS Laboratory reported $\delta^{18}O$ relative to the Vienna Mean Standard Ocean Water (VMSOW) standard and Isotech Laboratories reported $\delta^{18}O$ relative to the VPDB standard. The $\delta^{2}H$ of CH_4 was reported as compared to the VSMOW standard.

CO_2 would be the primary product of bacterial oxidation of CH_4, bacterial degradation of ketones, or combustion of organic matter. The $\delta^{13}C$ and $\delta^{18}O$ of CO_2 was determined by Isotech Laboratories. The cross-plot of the O and C isotope ratios for CO_2 is presented in Figure 18, along with the bounds of the isotopic ratios in CO_2 produced by combustion processes. The combustion processes area denotes isotopic fractionation due to combustion for a variety of biomass, fossil fuels, and wood materials (Schumacher et al. 2011). Thus, the isotopic signatures of CO_2 from site samples are inconsistent with a combustion source.

The $\delta^{13}C$ and $\delta^{2}H$ of CH_4 was determined by Isotech Laboratories for two samples from VMW-51I. Figure 19 presents a cross-plot of $\delta^{13}C$ and $\delta^{2}H$ for CH_4 of the VMW-51I data. Only data from two samples from VMW-51I are shown, because the CH_4 concentrations in

VEW-06I and VEW-07I were too low for analysis by Isotech Laboratories. These samples were subsequently submitted to the SoMAS Laboratory for analysis of $\delta^{13}C$ for CH_4. The isotopic signature of CH_4 in VMW-51I, VEW-06I, and VEW-07I is consistent with a bacterial source of CH_4 and is not consistent with combustion (Bogner et al. 1996; Whiticar et al. 1986). The highly negative $\delta^{13}C$ signature for CH_4 from VEW-06I and VEW-07I is indicative of a source of bacterial CH_4 distinct from that in VMW-51I and is consistent with ketone degradation. The CH_4 isotope data are discussed further in the Attachment C.

The $\delta^{13}C$ and $\delta^{18}O$ of CO was determined by the SoMAS Laboratory. Figure 20 presents the cross-plot of $\delta^{13}C$ and $\delta^{18}O$ of CO with isotopic fractionation of CO from various sources as compiled by Brenninkmeijer (1999). The isotopic signature of CO in VEW-06I is consistent with the isotopic signature expected for acetone (a ketone) in equilibrium with water (Sternberg and DeNiro 1983). VEW-07I and VMW-51I appear to reflect increasing contributions of CO from oxidation of CH_4 in addition to ketones, consistent with the relationships between the O_2, CO, CO_2, and CH_4 concentrations discussed earlier. In contrast, if the elevated CO in VEW-07I relative to VEW-06I was due to combustion, $\delta^{18}O$ of CO would be expected to shift toward that of atmospheric O_2 (+23 per mil) without a shift in the carbon isotope signature (Conny 1998). The observed shift between VEW-06I and VEW-07I is negative for both $\delta^{13}C$ and $\delta^{18}O$, consistent with contribution from microbial CH_4 oxidation and inconsistent with the addition of CO from combustion.

CONCLUSIONS

The overall conclusion from this study is that there is no evidence that the elevated subsurface temperature and elevated CO concentrations are due to combustion processes. In addition, the geochemical data indicate that the heating can be attributed to biochemical reactions in the vicinity of Zone A. Specific conclusions with respect to temperature, settlement, and geochemical analysis are presented below.

Temperature and Settlement

- No evidence of subsurface combustion is apparent from aerial thermal imagery and related observations

  - There are no areas of anomalously elevated surface temperatures, there are no areas showing excessive or sudden settlement, and there is no visible smoke or apparent odors

- There is no evidence of subsurface combustion from downhole temperature probes
  - Temperatures are well under 170°F, considered as the lower range of temperatures of concern.
  - There is no soot or combustion residue in SVE well casings
- Surface settlement continues
  - The settlement rates, as measured by ground survey, are similar to previous readings spanning a period of over 4 years
  - There are no abrupt or sharp changes at the surface topography, or obvious differential changes
  - There are tension cracks at the surface, but given the arid climate and dry soil conditions, lack of surface vegetation and lack of a shallow root system, the site is more susceptible to visible cracking,
  - There is no evidence, from testing or observations or from our elongation calculations, that the geomembrane cap is physically or mechanically compromised

Gas and Isotopic Analyses

- Temperatures are consistent with the range for bacterial activity
- Isotope signatures of CO_2 are indicative of bacterial production and not combustion
- CH_4 isotope signatures indicate bacterial origin typical of landfill gas
- Observed CO levels are in the range of landfill CO generation under aerobic conditions
- CO levels in VEW-06I are consistent with ketone degradation as the source
- CO levels in VEW-07I indicate additional contribution from bacterial CH_4 oxidation

RECOMMENDATIONS

One of the objectives of this study was to determine if the operational strategy for the SVE system should consider the Zone A subsurface heating condition. With the overall conclusion that the heating is not due to combustion processes occurring within the drummed waste or Balefill Area, an operational strategy utilizing shallow, intermediate, and deep SVE wells is reasonable. There is some risk associated with operating the intermediate wells given the elevated temperature at VEW-06I and higher temperatures to the north and east at VEW-05 and VMW-51I, but the intermediate wells also have the greatest potential for contaminant mass removal. Therefore the proposed long-term SVE system operation includes the intermediate wells based on Test No. 4 as follows:

- Shallow wells at 100 scfm
- Intermediate wells at 210 scfm (approximately 60 scfm; remainder dilution air)[3]
- Deep wells at 200 scfm

The stated flow rates are cumulative for each of the two shallow, intermediate, and deep wells. The actual flow rates at individual wells will be established based on field considerations and individual well capabilities.

Additionally, it is prudent to continue with some field monitoring to evaluate the subsurface heating condition under the revised SVE operation. Elements of the continuing field monitoring are as follows:

- Monitor extracted gas temperature at VEW-06I, VEW-07I, and VMW-51I
- Perform additional downhole temperature monitoring:
  - 6 months after establishment of the above-recommended SVE flow rates
  - If extracted gas temperatures exceed 130°F
- Add new settlement benchmarks
  - Locations based on recent observations (see Figure 2)
  - Survey on bimonthly basis through January 2013 and quarterly thereafter
- Continue monthly inspection of the Zone A cap and incorporate Balefill Area into monthly inspections
  - Observe surface expressions and conditions

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[3] In developing recommendations for continued operation of the SVE system, there is the potential for the intermediate wells to draw in air from the adjacent baled waste area but we believe the risk is relatively low and can be managed by recommended temperature, settlement, and gas monitoring programs.

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ATTACHMENTS

Attachment A	Zonge International Report
Attachment B	Aerial Infrared Thermal Survey
Attachment C	Methane Isotopic Analysis
Attachment D	Data Tables
Attachment E	Photos of Proposed Settlement Plate Locations

TABLES

Table 1
Schedule of Completed Activities

Task	Subtask	May				June															
		Week 1					Week 2					Week 3					Week 4				
		28	29	30	31	1	4	5	6	7	8	11	12	13	14	15	18	19	20	21	22
		M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F
Planning																					
	Revised Plan				X	X	X	X	X	X	X	X									
	Ecology Approval											X									
Heating Evaluation																					
	CIH/H&S Audit						X														
	Ongoing Testing																				
	Field Parameters - Active Wells (a)		X		X	x	X		X		X	X		X		X	X		X		X
	Field Parameters - Wells and Probes (b)		X		X		X		X			X		X			X		X		
	VOC Sampling (c)		X				X					X					X				
	$CO/CH_4/N_2O$ (d)		X		X		X		X			X		X			X		X		
	NO/NO_2 (e)				X		X		X	X		X		X			X		X		
	NH_3/HCN (e)				X		X		X			X		X			X		X		
	Isotopic Analyses:																				
	CO ($^{13}C/^{12}C$ and $^{18}O/^{16}O$) (f)																				
	CH4 and CO2 ($^{13}C/^{12}C$, $^{18}O/^{16}O$, and $^{1}H/^{2}H/^{3}H$) (g)																				
	Visual Inspection		X		X		X		X		X	X		X		X	X		X		X
	Thermal Imaging (h)																				
	Overflight																				
	Report Prep																				
	Settlement Plate Installation																				
	Zone A Location Recommenation																				
	Balefill Inspection and Recommendation																				
	Settlement Plate Installation and Survey (i)																				
	Vertical Temperature Profile																				
	Field Survey																				
	Data Evaluation																				
	Report Preparation																				

Task	Subtask	June					July														
		Week 5					Week 6					Week 7					Week 8				
		25	26	27	28	29	2	3	4	5	6	9	10	11	12	13	16	17	18	19	20
		M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F
Planning												Test 5 Terminated Interim Operation of SVE System to be Established with Agreement from Ecology									
	Revised Plan																				
	Ecology Approval																				
Heating Evaluation																					
	CIH/H&S Audit																				
	Ongoing Testing																				
	Field Parameters - Active Wells (a)	X		X		X	X			X		X		X		X	X				
	Field Parameters - Wells and Probes (b)	X		X			X			X		X		X							
	VOC Sampling (c)	X					X					X					X				
	$CO/CH_4/N_2O$ (d)	X		X			X			X		X		X							
	NO/NO_2 (e)	X		X			X			X		X		X			X				
	NH_3/HCN (e)	X																			
	Isotopic Analyses:																				
	CO ($^{13}C/^{12}C$ and $^{18}O/^{16}O$) (f)	X										X									
	CH4 and CO2 ($^{13}C/^{12}C$, $^{18}O/^{16}O$, and $^{1}H/^{2}H/^{3}H$) (g)	X										X									
	Visual Inspection	X		X		X	X		X		X		X	X							
	Thermal Imaging (h)																				
	Overflight			X	X																
	Report Prep					X	X	X	X	X	X	X	X								
	Settlement Plate Installation																				
	Zone A Location Recommenation																				
	Balefill Inspection and Recommendation																				
	Settlement Plate Installation and Survey (i)																				
	Vertical Temperature Profile																				
	Field Survey												X	X							
	Data Evaluation														X	X	X	X	X	X	X
	Report Preparation																				

Task	Subtask	July							August												
		Week 9					Week 10					Week 11					Week 12				
		23	24	25	26	27	30	31	1	2	3	6	7	8	9	10	13	14	15	16	17
		M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F
Planning																					
	Revised Plan																				
	Ecology Approval																				
Heating Evaluation																					
	CIH/H&S Audit																				
	Ongoing Testing																				
	Field Parameters - Active Wells (a)		x				X					X							X		
	Field Parameters - Wells and Probes (b)																				
	VOC Sampling (c)		x				X					X							X		
	$CO/CH_4/N_2O$ (d)																				
	NO/NO_2 (e)																				
	NH_3/HCN (e)																				
	Isotopic Analyses:																				
	CO ($^{13}C/^{12}C$ and $^{18}O/^{16}O$) (f)																				
	CH4 and CO2 ($^{13}C/^{12}C$, $^{18}O/^{16}O$, and $^{1}H/^{2}H/^{3}H$) (g)																				
	Visual Inspection																				
	Thermal Imaging (h)																				
	Overflight																				
	Report Prep																				
	Settlement Plate Installation																				
	Zone A Location Recommenation												X								
	Balefill Inspection and Recommendation																				
	Settlement Plate Installation and Survey (i)																				
	Vertical Temperature Profile																				
	Field Survey																				
	Data Evaluation																				
	Report Preparation	X	X	X	X																

Task	Subtask	August										September									
		Week 13					Week 14					Week 15					Week 16				
		20	21	22	23	24	27	28	29	30	31	3	4	5	6	7	10	11	12	13	14
		M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F
Planning																					
	Revised Plan																				
	Ecology Approval																				
Heating Evaluation																					
	CIH/H&S Audit																				
	Ongoing Testing																				
	Field Parameters - Active Wells (a)	X					X					X					X				
	Field Parameters - Wells and Probes (b)																				
	VOC Sampling (c)	X					X					X					X				
	$CO/CH_4/N_2O$ (d)																				
	NO/NO_2 (e)																				
	NH_3/HCN (e)																				
	Isotopic Analyses:																				
	CO ($^{13}C/^{12}C$ and $^{18}O/^{16}O$) (f)																				
	CH4 and CO2 ($^{13}C/^{12}C$, $^{18}O/^{16}O$, and $^{1}H/^{2}H/^{3}H$) (g)																				
	Visual Inspection																				
	Thermal Imaging (h)																				
	Overflight																				
	Report Prep																				
	Settlement Plate Installation																				
	Zone A Location Recommenation																				
	Balefill Inspection and Recommendation															X					
	Settlement Plate Installation and Survey (i)																				X
	Vertical Temperature Profile																				
	Field Survey																				
	Data Evaluation																				
	Report Preparation																				

Table 1
Schedule of Completed Activities

		May				June																					July																					
		Week 1					Week 2					Week 3					Week 4					Week 5					Week 6					Week 7					Week 8					Week 9					Week 10	
Task	**Subtask**	28	29	30	31	1	4	5	6	7	8	11	12	13	14	15	18	19	20	21	22	25	26	27	28	29	2	3	4	5	6	9	10	11	12	13	16	17	18	19	20	23	24	25	26	27	30	31
		M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T
Technical Memo Preparation																																																
	IWAG Review																																					X	X	X	X	X	X	X	X	X	X	X
	Presentation to Ecology																																															
	Tech Memo Preparation																																															
	Ecology Submittal																																															

		August																							September									
		Week 10			Week 11					Week 12					Week 13					Week 14					Week 15					Week 16				
Task	**Subtask**	1	2	3	6	7	8	9	10	13	14	15	16	17	20	21	22	23	24	27	28	29	30	31	3	4	5	6	7	10	11	12	13	14
		W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F	M	T	W	Th	F
Technical Memo Preparation																																		
	IWAG Review	X	X	X	X																													
	Presentation to Ecology					X																												
	Tech Memo Preparation						X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	Ecology Submittal																																	X

Field Parameters - Vacuum, flow, temperature, LEL, CO2/O2/balance. Gas composition measurements with Landtec GEM 2000 portable landfill gas analyzer.

(a) VEW-06S, VEW-06I, VEW-06D, VEW-07S, VEW-07I, VEW-07D
(b) Parameters from VMW-51I and vacuum measurements from VMW-50S, VMW-51D, VEW-01, VMW-02D, VEW-04, VEW-05, and the 10 VMPs
(c) VOC samples collected only from six wells under active extraction
(d) Tedlar bag samples from VEW-06I, VEW-07I, and VMW-51I submitted to ALS, Simi Valley, California for 24-hour TAT
(e) Adsorber tube samples from VEW-06I, VEW-07I, and VMW-51I submitted to ALS, Salt Lake City, Utah for 24-hour TAT
(f) Tedlar bag samples from VEW-06I, VEW-07I, and VMW-51I submitted to State University of New York - Stonybrook, Prof. John Mak.
(g) Tedlar bag samples from VEW-06I, VEW-07I, and VMW-51I submitted to IsoTech
(h) Performed by Stockton Infrared Thermographic Services, Randleman, North Carolina and Cascade Thermal, Inc.
(i) Settlement plate surveying schedule to be determined based on Ecology approval. Quarterly as part of regular cap monitoring and presented in quarterly reports.

Table 2
Summary of Field Parameters and Analyses

Analyte	Instrument	Analytical Method	Method Detection Limit	QA/QC Procedures
CO_2	Landtec GEM 2000	Dual Wavelength Infared Cell	0%	Calibration: Fresh Air Daily. Monthly with 50% CH_4/35%CO_2/N as Balance
O_2	Landtec GEM 2000	Electrochemical Cell	0%	Calibration: Fresh Air Daily. Monthly with 4% O_2/N as Balance
LEL	Landtec GEM 2000	Calculated for CH_4	0%	NR
Vacuum	Magnahelic Gage	NA	0.1 inches H_20	NR
Air Flow	DS-300 and Magnahelic Gage	NA	0.1 inches H_20	NR
Temperature	In-line Direct Read Thermometer	NA	1 deg F	NR
Ionizable Volatile Compounds	Photoionization Detector	10.6 meV bulb	1 ppmV	Daily 2-point Calibration with Zero Gas and 100 ppmV Isobutylene

Notes:

NR - not required	meV - millielectron volt
NA - not applicable	ppmV - parts per million by volume

Table 3
Summary of SVE System Vapor Analyses
Wells VEW-6I, VEW-7I, and VMW-51I

Analyte	Collection Method	Analytical Method	Method Detection Limit	Laboratory Location	Duplicates	QA/QC Procedures
CO	Tedlar Bag	25C Modified/TGNMO	5 ppmV	ALS - Simi Valley, CA	1 dup. per SDG[b]	MS/MSD[c]
CH_4	Tedlar Bag	25C Modified/TGNMO	0.5 ppmV	ALS - Simi Valley, CA	1 dup. per SDG[b]	MS/MSD[c]
N_2O	Tedlar Bag	Modified EPA 3C	25 ppmV	ALS - Simi Valley, CA	1 dup. per SDG[b]	MS/MSD[c]
NH_3	Sorbent Tube	NIOSH 6015	1.2 µg[a]	ALS - Salt Lake City, UT	1 dup. per SDG[b]	MS/MSD[c]
HCN	Sorbent Tube	NIOSH 6010	0.21 µg[a]	ALS - Salt Lake City, UT	1 dup. per SDG[b]	MS/MSD[c]
NO	Sorbent Tube (3 stage)	NIOSH 6014	0.52 µg[a]	ALS - Salt Lake City, UT	1 dup. per SDG[b]	MS/MSD[c]
NO_2	Sorbent Tube (3 stage)	NIOSH 6014	0.79 µg[a]	ALS - Salt Lake City, UT	1 dup. per SDG[b]	MS/MSD[c]

Notes:

(a) - Analyte mass/tube. Concentration dependent upon volume of air or vapor drawn through the tube during sampling.

(b) - Blind field duplicate. One duplicate for each sample delivery group (SDG).

(c) - MS/MSD - Laboratory matrix spike/matrix spike duplicate to assess method accuracy and precision.

µg - micrograms

Table 4
Summary of Isotopic Analyses

Analyte	Laboratory	Laboratory Method	Method Detection Limit	QA/QC
$\delta^{13}C\ CO_2$	Isotech Laboratories, Inc	Offline GC-C-DI IRMS[1]	Concentration Limits Vary[3] Laboratory Precision 0.1 per mil ($^{0}/_{00}$)	Laboratory QA/QC Procedures: QA/QC a minimum of 20% of all analyses Instruments regularly calibrated with NIST[5] and IAEA[6] standards >10% of analyses are Internal check standards with compositions similar to the samples being analyzed. >10% of all analyses are sample duplicates.
$\delta^{18}O\ CO_2$	Isotech Laboratories, Inc	Offline GC-C-IRMS	Concentration Limits Vary	
$\delta\ ^{13}C\ CH_4$	Isotech Laboratories, Inc	Offline GC-C-IRMS	Concentration Limits Vary Precision 0.1 $^{0}/_{00}$	
$\delta^{2}H\ CH_4$	Isotech Laboratories, Inc	Offline GC-C-IRMS	Concentration Limits Vary Precision 1.0 $^{0}/_{00}$	
$\delta\ ^{13}C\ CO$	SoMAS, Stony Brook Univ.	CF-IRMS[2]	Concentration Limits Vary, 60-140 ppbv CO in air Precision 0.2 $^{0}/_{00}$[4]	Laboratory's Standard QA/QC Procedures. Duplicate analysis performed
$\delta\ ^{18}O\ CO$	SoMAS, Stony Brook Univ.	CF-IRMS	Limits Vary, 60-140 ppbv CO in air Precision 0.6 $^{0}/_{00}$[4]	

Table notes:

1. Gas Chromatographic Separation, Combustion, Dual Inlet Isotope Ratio Mass Spectrometry. Offline indicates that the GC separation step is performed separately and samples are then transferred to the IRMS.
2. Continuous Flow GC-C-IRMS to increase sensitivity.
3. Concentration limits for a given sample depend on mass recovery for input into the IRMS. Very low mass recoveries decrease the precision of the isotopic fractionation measurement, and would be reported as estimated values or non-detects by the laboratory.
4. Reported in Mak and Yang 1998; Wang and Mak 2010.
5. National Institute of Standards and Testing
6. International Atomic Energy Agency

FIGURES

Q:\Jobs\100722-01_PascoWA\Maps\Memo\TechMemo_Balefill_Portrait.mxd nkochie 9/7/2012 2:45:41 PM

ANCHOR QEA

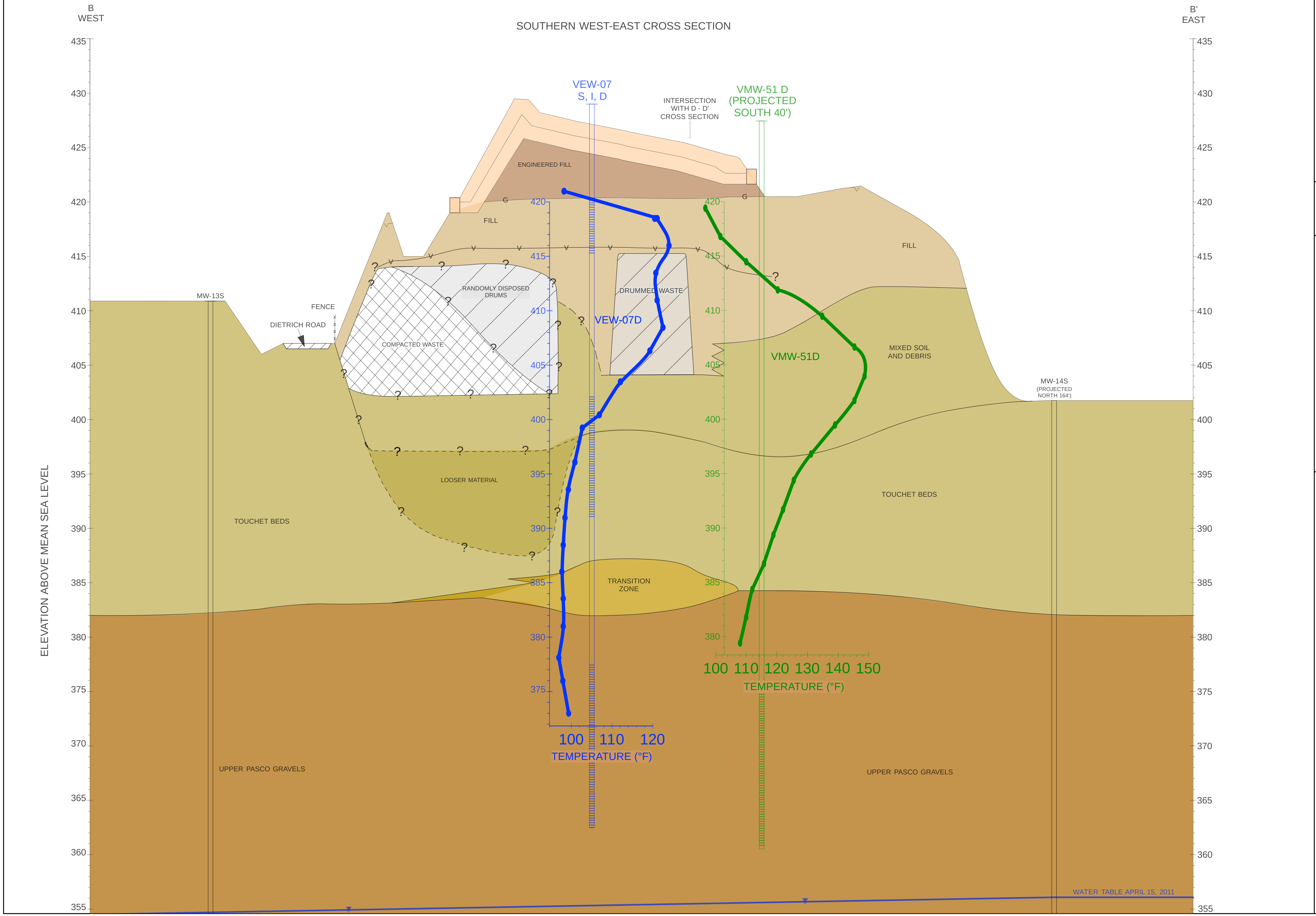
Figure 1
Zone A Heating Evaluation
Sampling Locations
Pasco, WA

ANCHOR QEA

Feet
0 75 150

Figure 2
Proposed Settlement Plate Locations
Pasco, WA

Figure 3
Interior View of VEW-05
Zone A Heating Evaluation
Pasco Sanitary Landfill Site



VERTICAL SCALE:
6X VERTICAL EXAGERATION

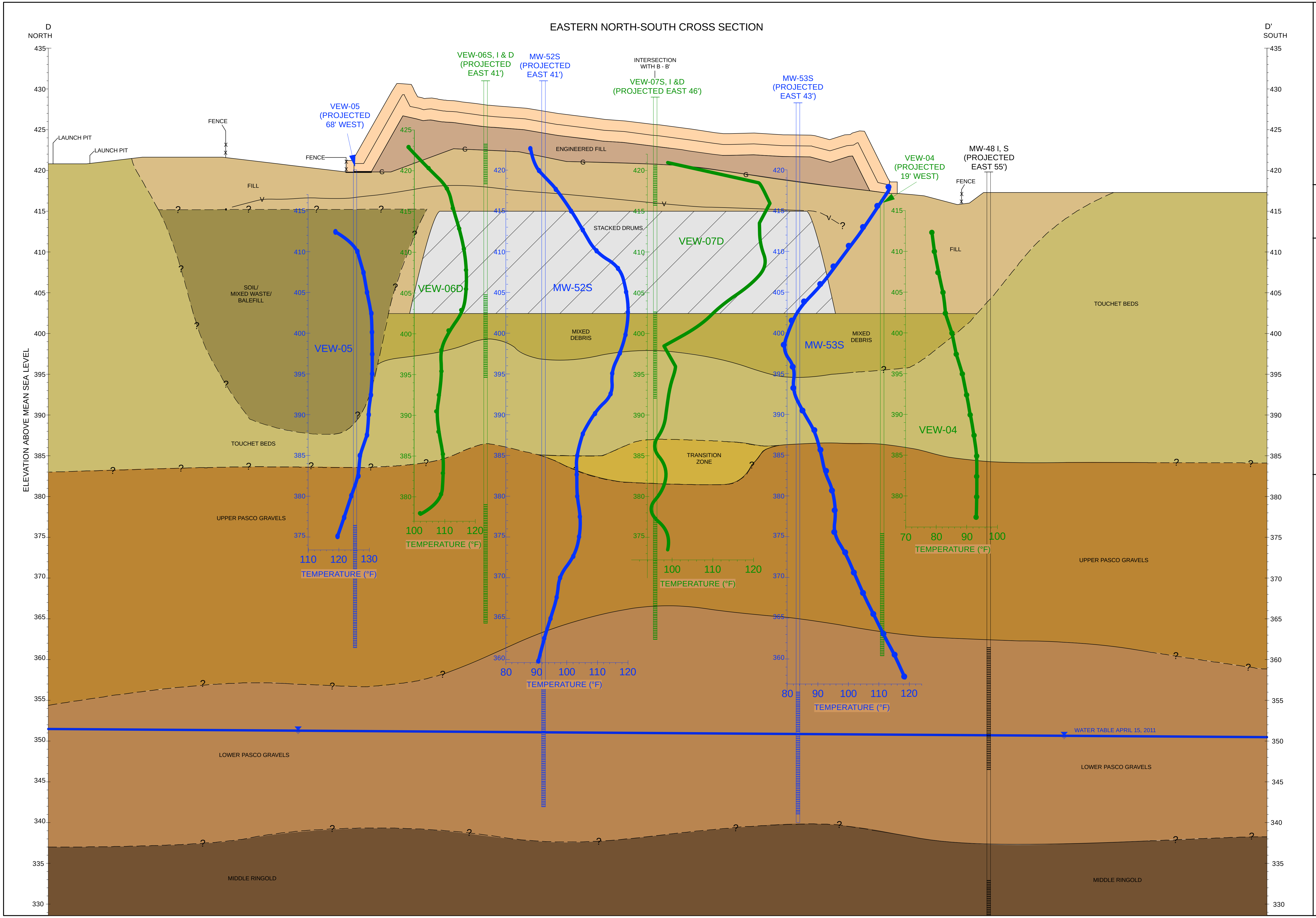
PROJECT	03911.5
PREPARED FOR	IWAG GROUP III
LOCATION	1901 DIETRICH ROAD PASCO, WASHINGTON
DRAWN BY	MMH
REVIEWED BY	MJR
DATE	9/10/2012

ENVIRONMENTAL PARTNERS INC

295 NE Gilman Boulevard, Suite 201
Issaquah, Washington 98027

FIGURE 4

DOWNHOLE TEMPERATURE PROFILES
SOUTHERN WEST-EAST CROSS SECTION



PROJECT
03911.5

PREPARED FOR
IWAG GROUP III

LOCATION
1901 DIETRICH ROAD
PASCO, WASHINGTON

DRAWN BY
MMH

REVIEWED BY
MJR

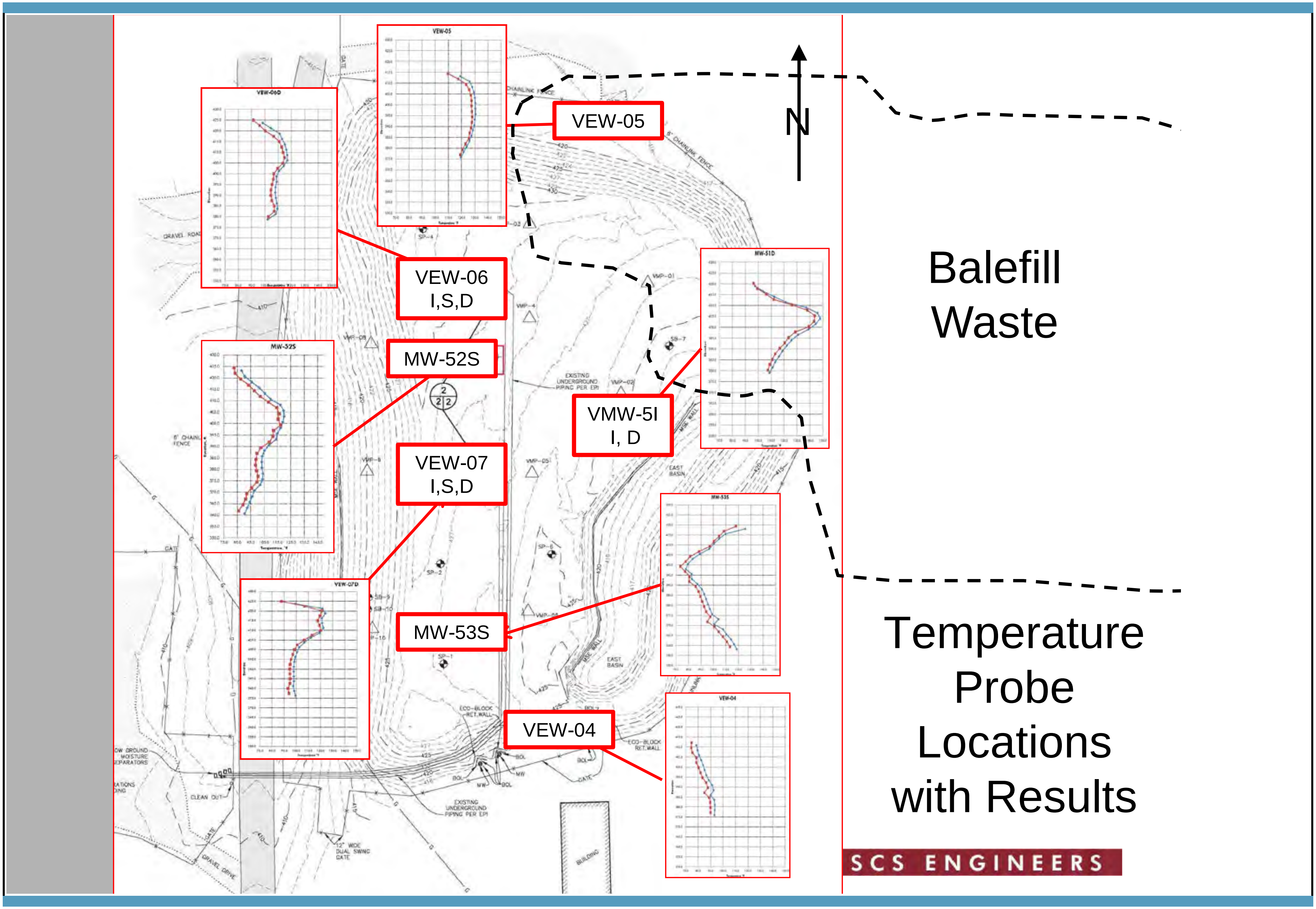
DATE
9/10/2012

E N V I R O N M E N T A L
P A R T N E R S I N C
295 NE Gilman Boulevard, Suite 201
Issaquah, Washington 98027

FIGURE 5

DOWNHOLE TEMPERATURE PROFILES
EASTERN NORTH-SOUTH CROSS SECTION

VERTICAL SCALE:
6X VERTICAL EXAGERATION



Balefill Waste

Temperature Probe Locations with Results

Figure 6
Downhole Temperature Profiles—Plan View
Zone A Heating Evaluation
Pasco Sanitary Landfill Site

Feet
0 30 60

Figure 7
Zone A Heating Evaluation
Sampling Locations
Pasco, WA

Q:\Jobs\100722-01_PascoWA\Maps\Memo\TechMemo_TempElev.mxd nkochie 10/23/2012 10:57:38 AM

Q:\Jobs\100722-01_PascoWA\Maps\Memo\TechMemo_TempElev.mxd nkochie 10/23/2012 10:58:55 AM

ANCHOR QEA

Feet
0 30 60

Figure 8
Zone A Heating Evaluation
Sampling Locations
Pasco, WA

ANCHOR QEA

Figure 9

VEW-06I –Temperature, CO, O2, CO2 and Methane Time Series
Zone A Heating Evaluation
Pasco Sanitary Landfill Site

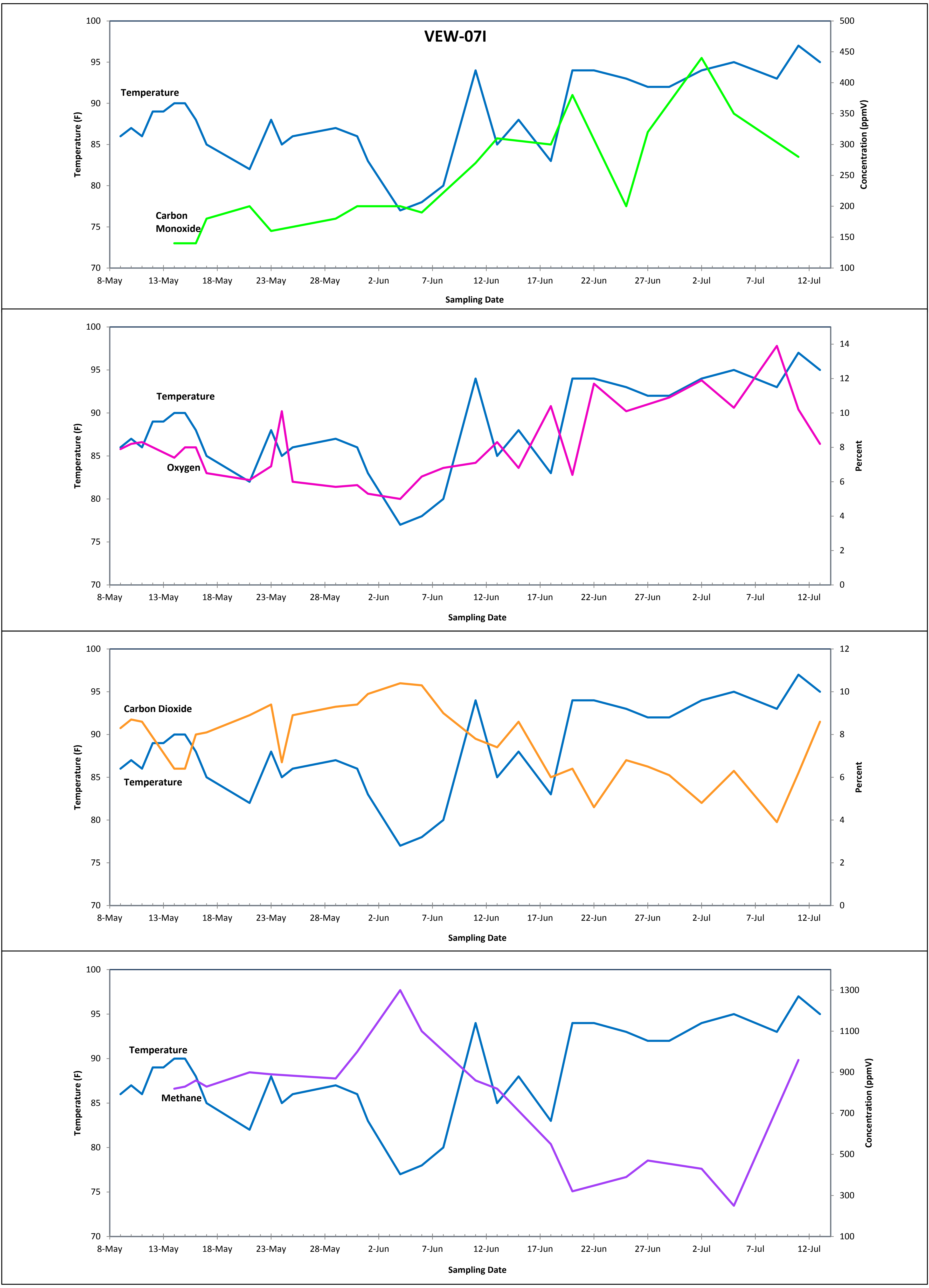


Figure 10
VEW-07I –Temperature, CO, O2, CO2 and Methane Time Series
Zone A Heating Evaluation
Pasco Sanitary Landfill Site

Figure 11
VEW-51I –Temperature, CO, O2, CO2 and Methane Time Series
Zone A Heating Evaluation
Pasco Sanitary Landfill Site

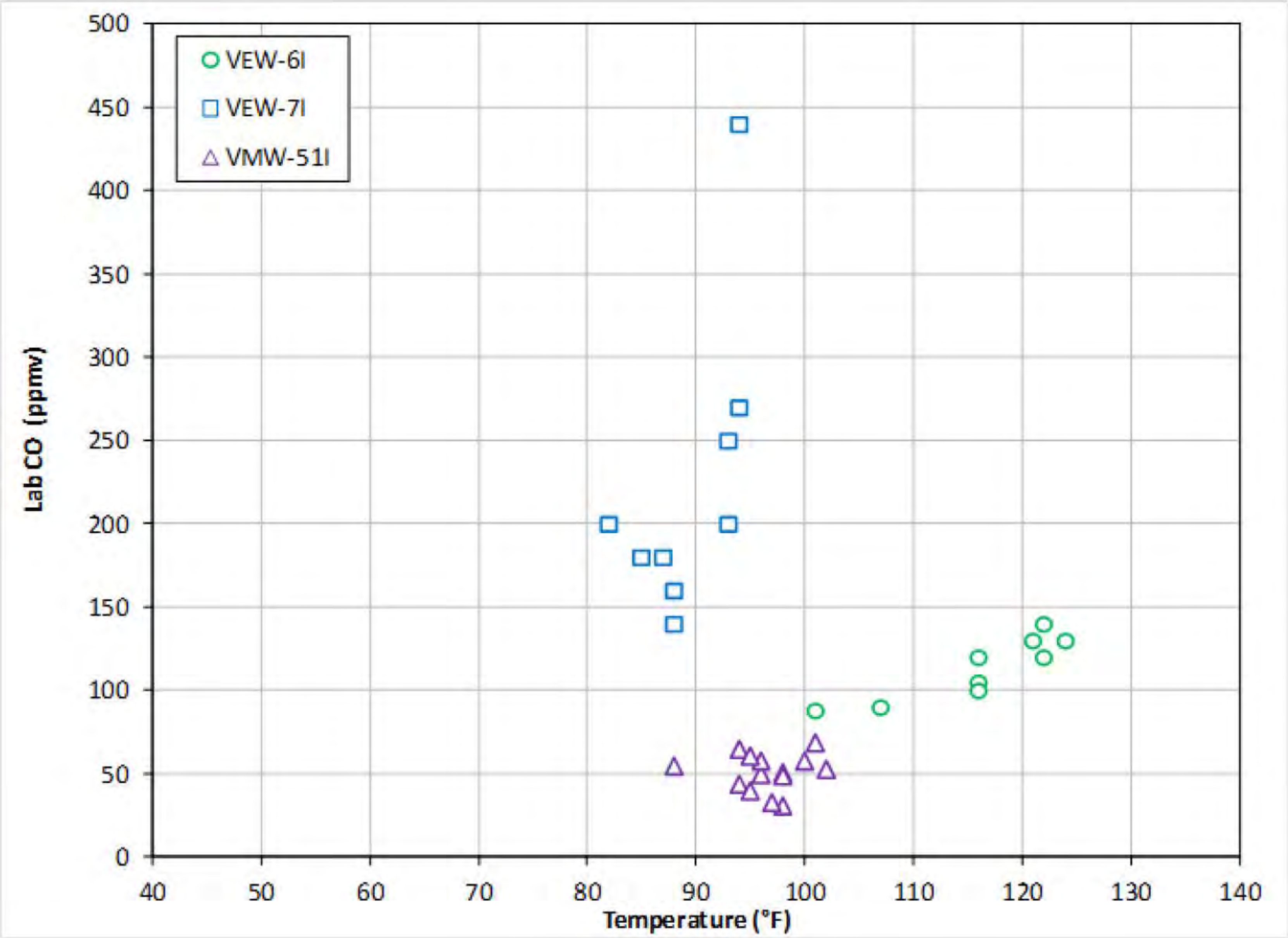


Figure 12
Carbon monoxide (analytical laboratory) concentration versus temperature for VEW-06I, VEW-07I, and VMW-51I
Zone A Heating Evaluation
Pasco Sanitary Landfill Site

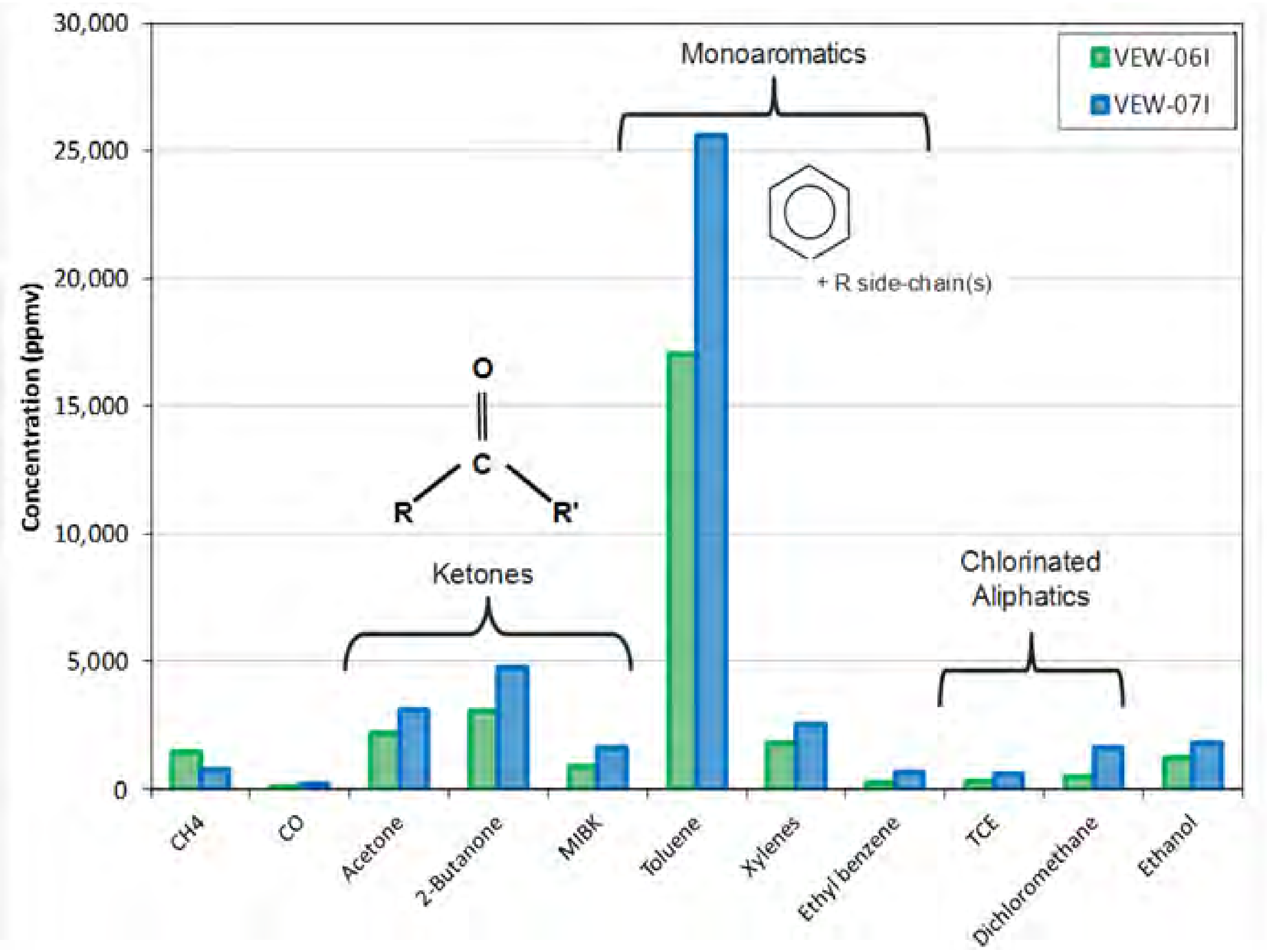


Figure 13
Concentrations (in ppm by volume) of CH_4, CO, and Predominant VOCs in VEW-06I and VEW-07I
Zone A Heating Evaluation
Pasco Sanitary Landfill Site

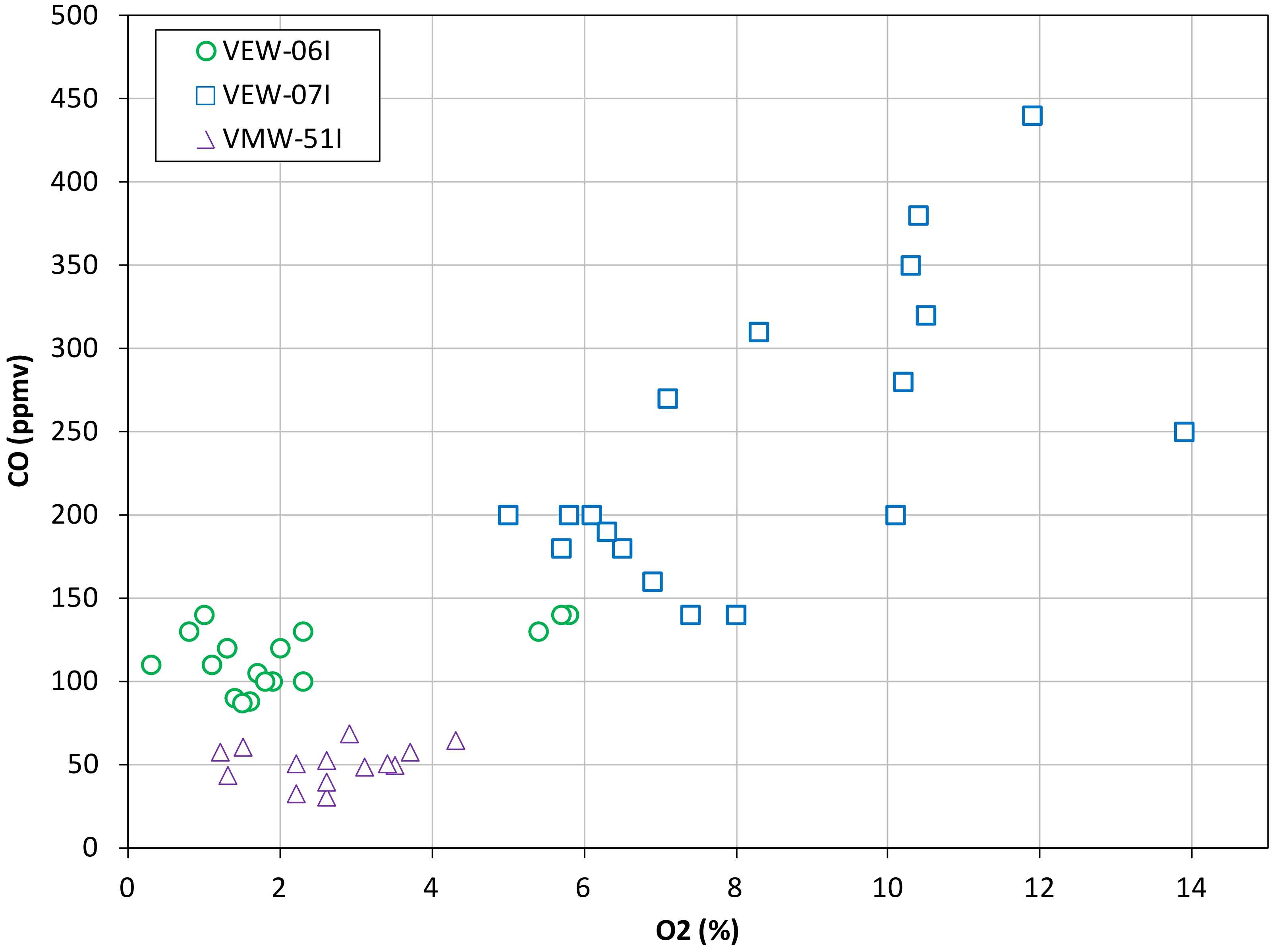
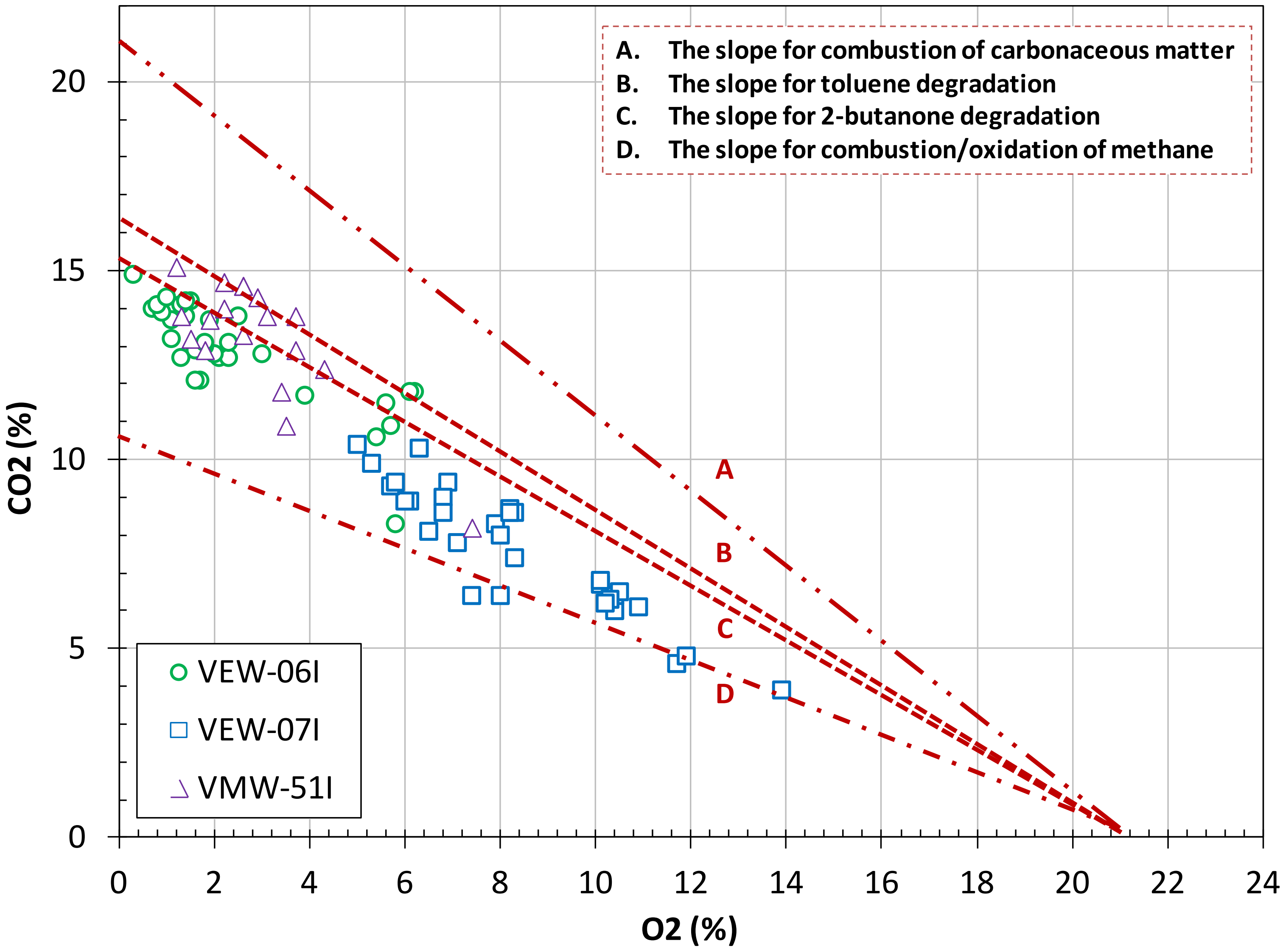


Figure 14

Relationship between CO Concentration and Percent O_2 for VEW-06I, VEW-07I, and VMW-51I

Zone A Heating Evaluation

Pasco Sanitary Landfill Site



Dashed lines indicates the stoichiometric relationship for combustion of carbonaceous material (slope -1, extends from air [x=21, y=0.03] to [x=0, y=21.03]) (A); toluene oxidation (slope -7/9, extends to[x=0, y=16.36]) (B); 2-butanone oxidation (slope -8/11, extends to [x=0, y=15.3]) (C); and methane oxidation (slope -1/2, extends to [x=0, y=10.53]) (D).

ANCHOR QEA

Figure 15

Relationship between CO_2 (%) and O_2 (%) in VEW-06I, VEW-07I, and VMW-51I

Zone A Heating Evaluation

Pasco Sanitary Landfill Site

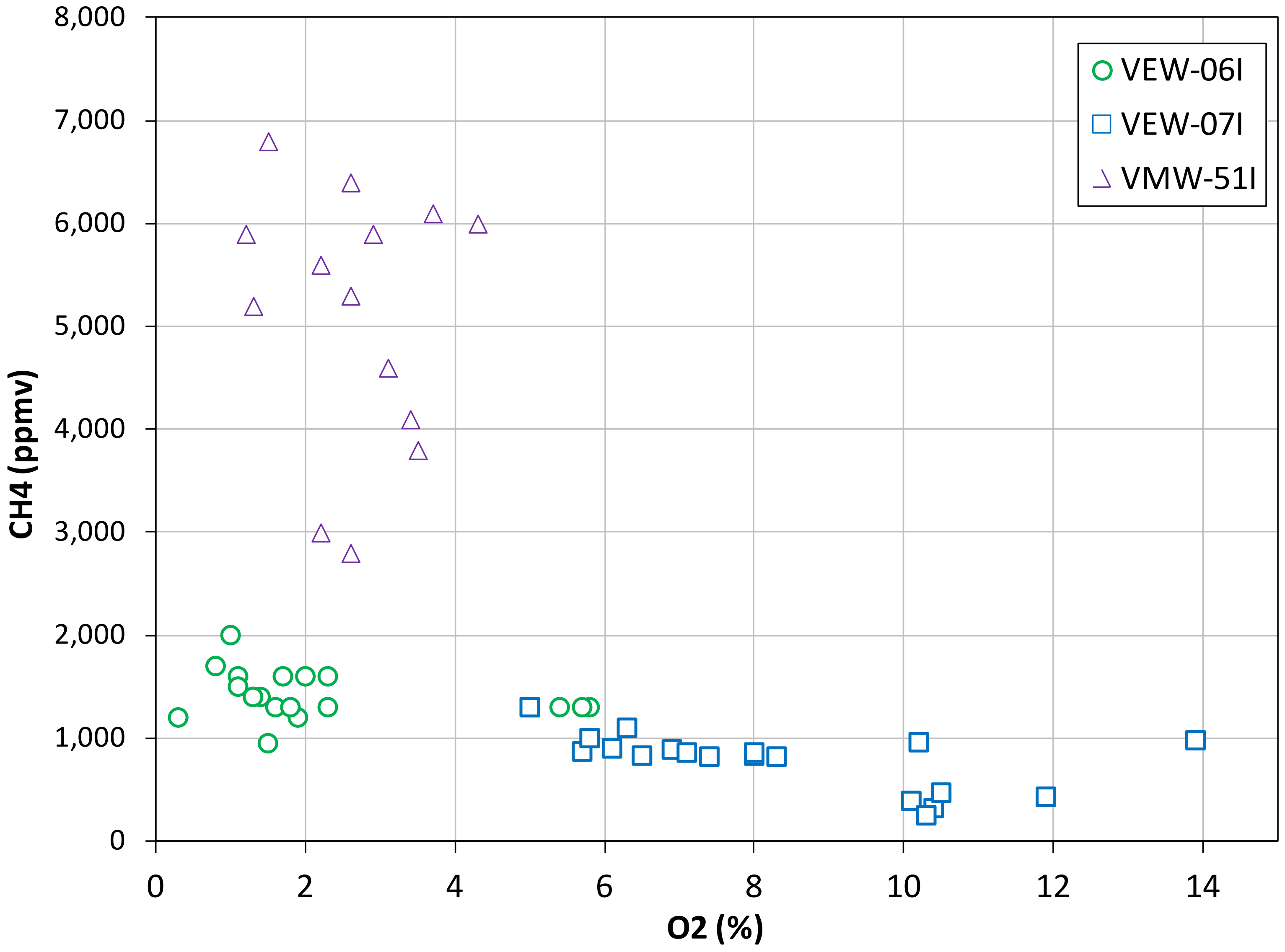
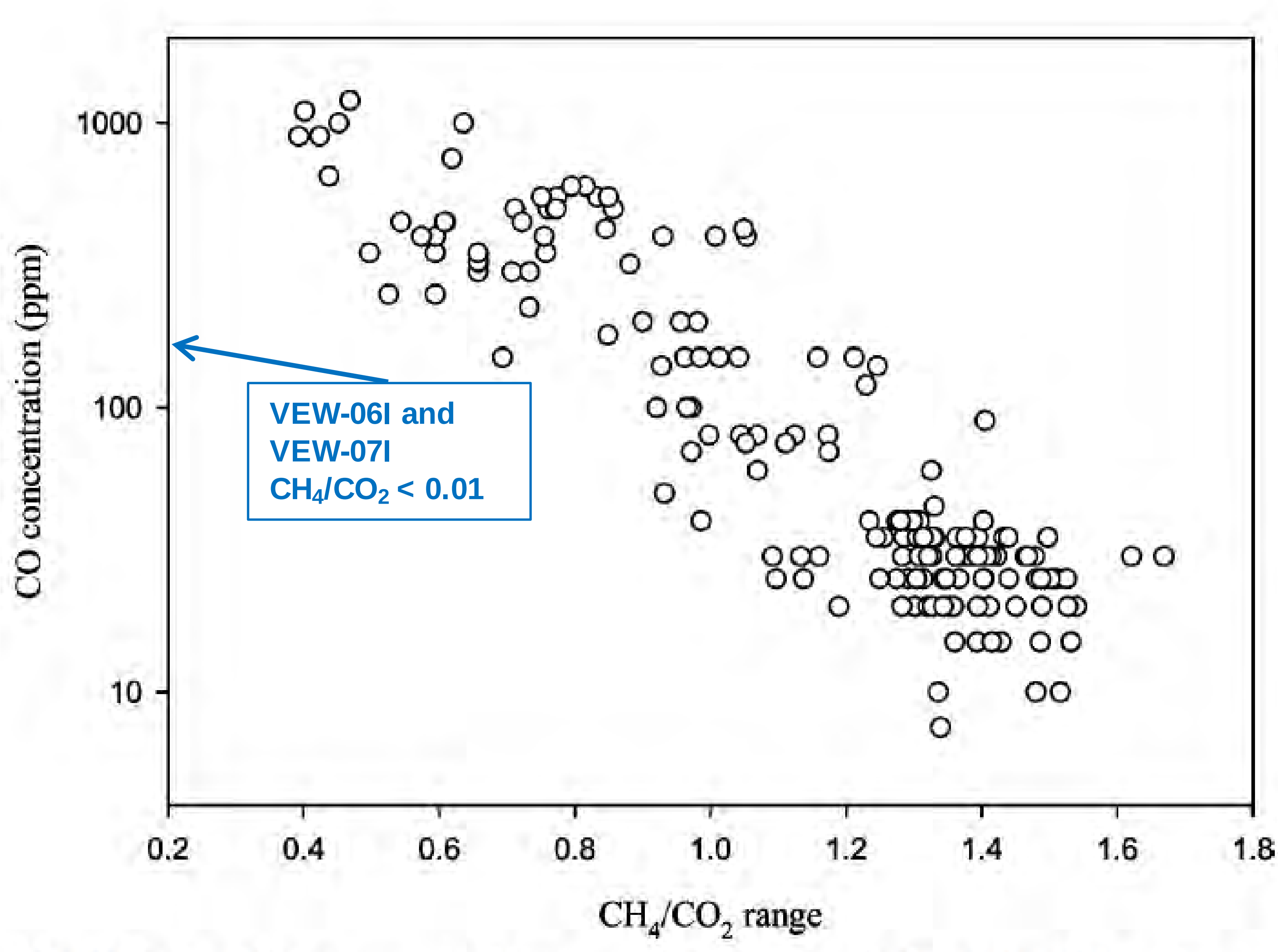


Figure 16

Relationship between CH_4 Concentration and Percent O_2 for VEW-06I, VEW-07I, and VMW-51I

Zone A Heating Evaluation

Pasco Sanitary Landfill Site



VEW-06I and VEW-07I $CH_4/CO_2 < 0.01$

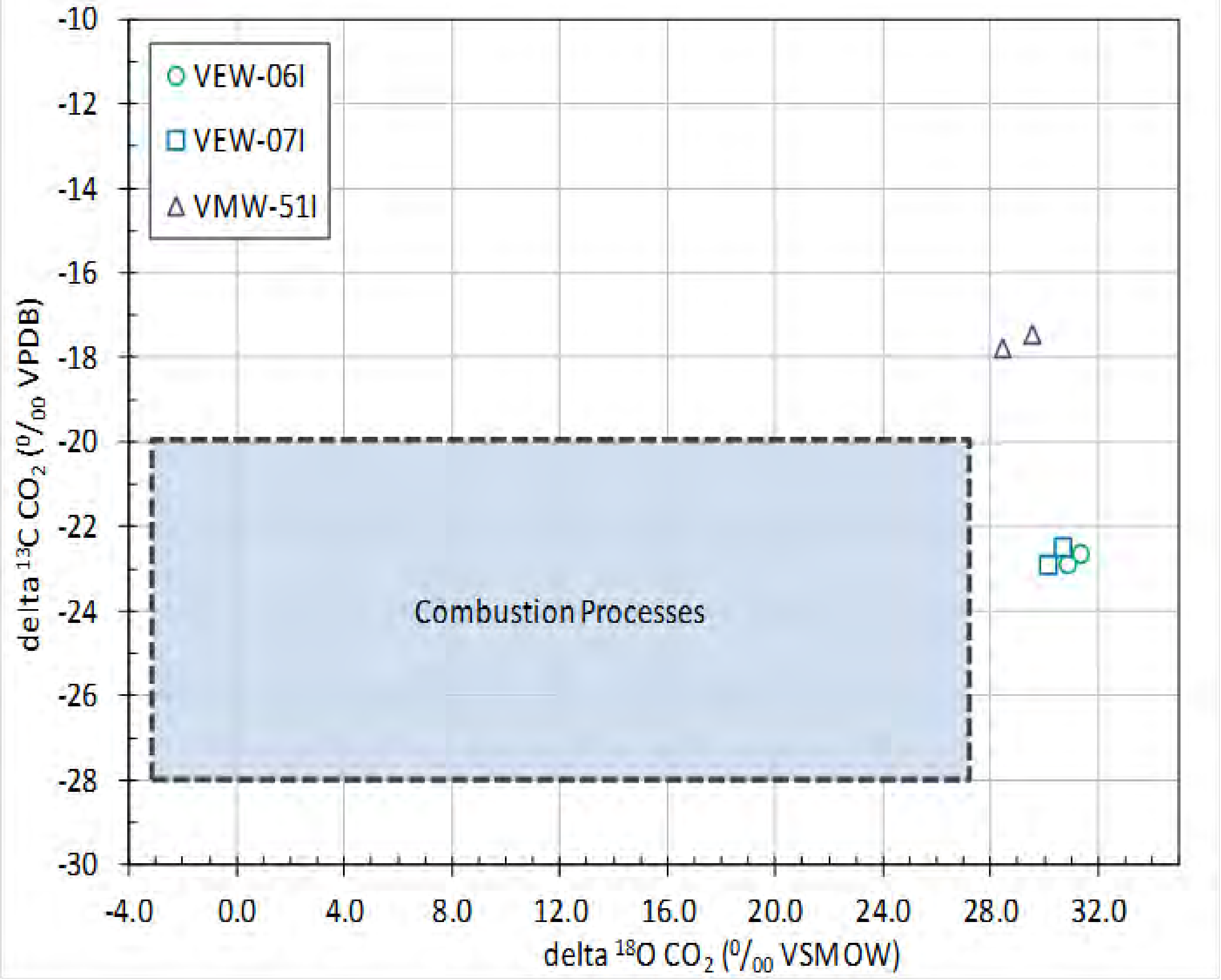
CH_4 concentrations decrease while CO_2 concentrations increase during the aerobic stabilization process (from Powell et al. 2006)

Figure 17

Relationship between CO Concentration and the CH_4/CO_2 Ratio (as a measure of aerobic activity)

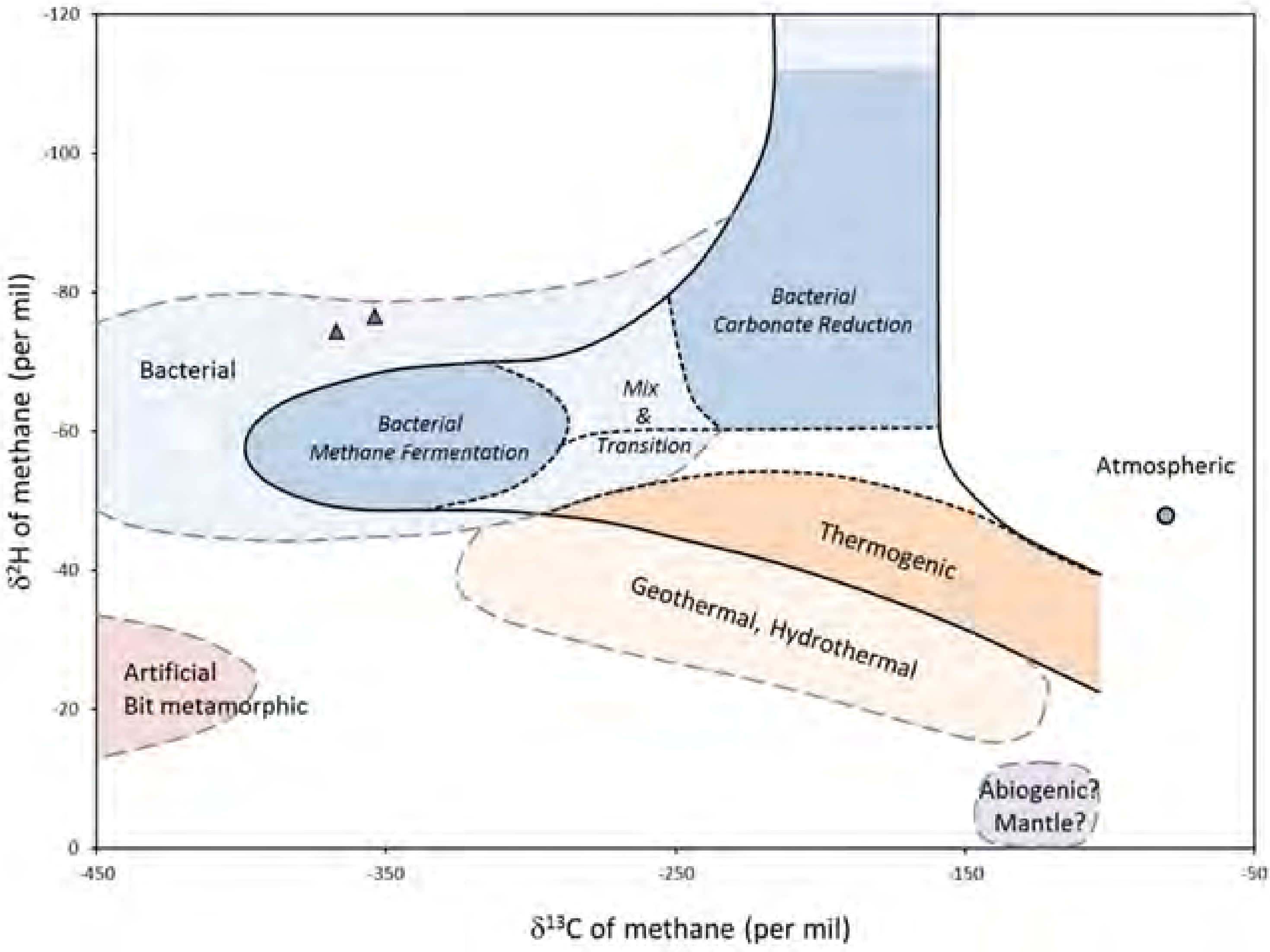
Zone A Heating Evaluation

Pasco Sanitary Landfill Site



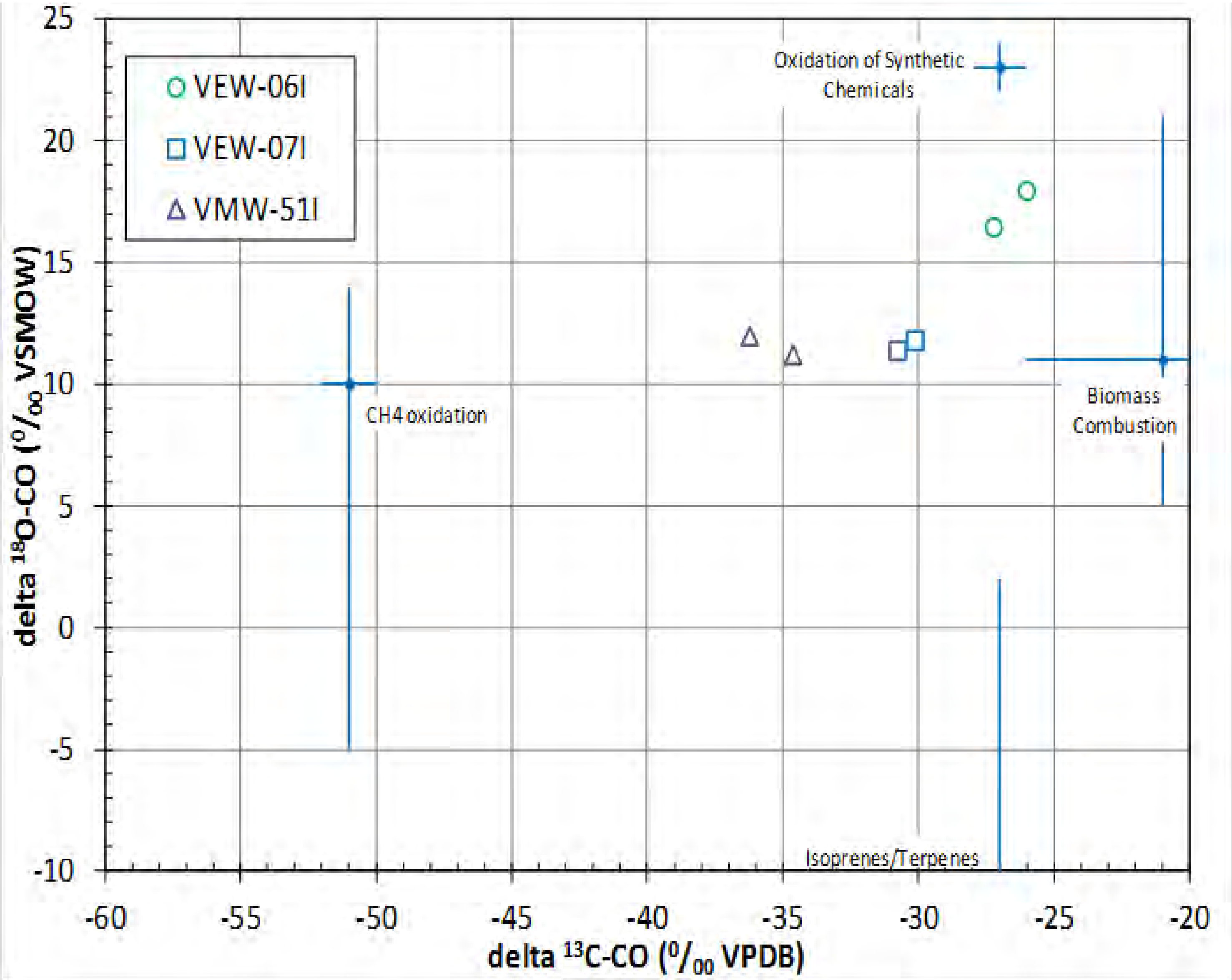
Blue dashed box indicates the isotopic signature of CO_2 for combustion processes (after Schumacher et al. 2011)

Figure 18
Isotopic Signature of CO_2 from VEW-06I, VEW-07I, and VMW-51I
Zone A Heating Evaluation
Pasco Sanitary Landfill Site



The approximate fields for fractionation by various processes is outlined after Whiticar 1999

Figure 19
Isotopic Signature of CH_4 from VMW-51I
Zone A Heating Evaluation
Pasco Sanitary Landfill Site



Blue crosshairs indicate the isotopic range of carbon and oxygen isotopes for the specified processes (after Brenninkmeijer 1999)

Figure 20

Isotopic Signature of CO from VEW-06I, VEW-07I, and VMW-51I

Zone A Heating Evaluation

Pasco Sanitary Landfill Site

ATTACHMENT A
ZONGE INTERNATIONAL REPORT

Zonge
TRUSTED GEOPHYSICS

Zonge International, Inc.
Parkside Business Center, Bldg. 1-B
3866 SW Nimbus Avenue
Beaverton, OR 97008

July 26, 2012
Ref: 12130

Thomas C. Morin, L.G. - President/Principal
Environmental Partners, Inc.
295 NE Gilman Boulevard, Suite 201
Issaquah, Washington 98027

Re: ***Borehole Temperature Measurements***
Pasco Landfill
Pasco Washington

Dear Mr. Morin,

This letter presents results and procedures for borehole casing temperature logs in seven (7) vapor extraction and vapor monitoring wells at the Pasco Landfill, Pasco, Washington. Borings listed in Table 1 below were logged July 10 and 11, 2012. Boring temperature logs are included as Figures 1-7.

Boring ID	Depth logged (feet bgl)	Ground elevation (feet msl)	Casing material
VEW-04	40.5	418.0	PVC
VEW-05	43.5	418.5	PVC
VEW-06D	50.8	429.0	Stainless
VEW-07D	53.4	426.9	Stainless
VMW-51D	44.3	423.7	Stainless
MW52S	67.7	428.3	Stainless
MW-53S	67.8	425.8	Stainless

Table 1: Borings Logged, July 2012

METHODOLOGY

All borings were logged above the water table. This necessitated constructing a downhole probe which would hold a temperature sensing transducer against the boring wall to acquire temperature data. Borings were cased with 4 inch stainless steel, except for VEW-04 and VEW-05 which were cased with 4 inch PVC. All logging was done above the screened intervals, generally 45-65 feet below ground level (bgl).

Borehole Probe

Zonge International, Inc. fabricated a temperature probe shown in Photo 1. The probe is constructed around a BHG3 downhole geophone (Photo 2) manufactured by GeoStuff of Lincoln, CA. The BHG3 has an expandable spring to lock the probe against the borehole wall.

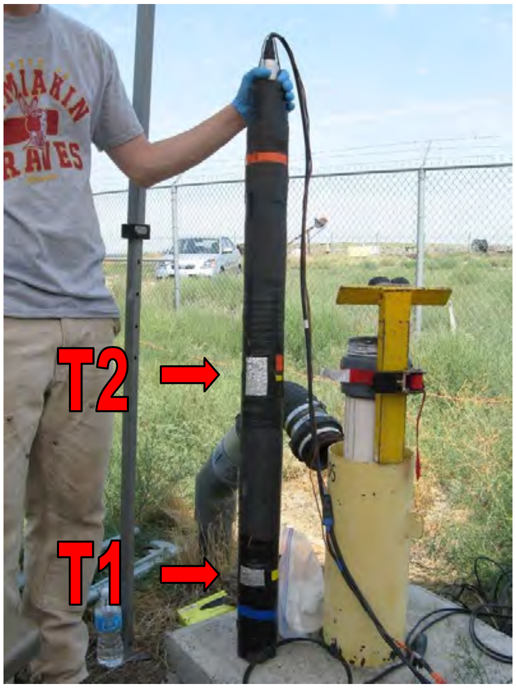


Photo 1: Downhole Temperature Probe

Photo 2: BHG3 Downhole Geophone

The BHG3 is 1.75 inches in diameter, excluding the spring and constructed with a stainless steel housing. The BHG3 was surrounded with ¾ inch thick black styrofoam pipe insulation in order to thermally isolate the BHG3 from the borehole wall. Temperature sensors were taped to the outside of the styrofoam opposite the spring. A piece of hard plastic was placed between the styrofoam and the sensor in order to push the sensor out and assure coupling with the borehole wall.

The BHG2 control cable provides power to expand and contract the spring. It is also calibrated with tape markings at 2.5 foot intervals.

Temperature Sensor

Temperature sensors were two Type J (iron/constantan) thermocouples. The two sensors were separated by 1.25 feet on the borehole probe (Photo 1). Thermocouples were attached to 100 feet of 16 gauge stranded thermocouple lead in wire (iron/constantan).

The signal was read at the surface using an EXTECH Instruments 2-channel thermometer/data logger (Model# 421509).

Initially (logging MW-52S and MW-53S, Trips 1 & 2) a bare thermocouple was used (Photo 3). Following those logs a small pad of aluminum was added, embedding the thermocouple between layers of aluminum foil. The pad was intended to increase the thermal coupling between the borehole wall and the thermocouple. Following that modification, MW-53S was logged again (Trip 3) with similar results to Trip 2. The foil modification was maintained for the rest of the boreholes.

Photo 3: Bare Thermocouple

Photo 4: Foil Embedded Thermocouple

Procedures

All borings were logged from the bottom to the top. The probe was lowered to the bottom depth, just above the screened interval, and the temperature allowed to stabilize for up to 15 minutes. Temperatures of each sensor were logged and the probe moved up the hole 2.5 feet. At each interval, the temperature was allowed to stabilize. Stabilization was attained after less than 1 minute in low gradient areas, but sometimes required 2 minutes or more. Temperature was judged to be stable when it was changing less than 1 °F per minute. Judgment regarding stabilization was qualitative and subjective in nature.

RESULTS

Temperature data logs are presented in Figures 1 to 7. Plots show data from the lower sensor, T1, and the upper sensor, T2, each plotted at the sensor depth bgl. Readings were made at 2.5 foot intervals, with the sensors separated by 1.25 feet. The plots also show a "T_0 –Composite" curve which is our preferred temperature curve as discussed below.

Data from the two sensors shows a lag in the temperature between T1 (the lower sensor) and T2 (the upper sensor). We attribute this to the thermal mass or heat capacity of the styrofoam. While the black styrofoam is an excellent insulator, it also holds its heat. Therefore, the styrofoam may affect the borehole wall, and/or mute the effect of the borehole wall on the sensor. Minor differences in construction/installation of the two sensors and hence their coupling with the borehole wall led to the differences in measured temperature. The two thermocouples were identical, and when placed together in an ice bath, or constant temperature solution, they tracked within one degree Fahrenheit (F) of each other.

Borehole VMW 51D was logged twice, the first logging at 16:20, July 11 and the second at 10:00, July 12. Measured temperatures for the lower sensor from the two "trips" were generally within 2°F. MW-53S was also logged twice with the measured temperatures for the lower sensor from the two "trips" generally within 5°F. However, one of those trips was early in the survey, prior to installing the foil pad around the thermocouple.

The lower sensor appeared more responsive to temperature changes and hence we rely more heavily on the lower sensor. Hence, our "Composite" temperature is taken from the lower sensor, or where the boring was logged twice (2 trips) an average (mean) of the two logs was used.

CONCLUSIONS AND RECOMMENDATIONS

The survey successfully measured borehole temperatures in the seven vapor extraction wells, with temperatures varying from 80 °F to 150 °F. While the trends are real and repeatable, the accuracy seems to be ±2 °F, with the relative accuracy, between two adjacent readings, closer to ±1 °F.

To obtain reading with more accuracy, the borehole probe could be modified. We would recommend doing away with the black styrofoam pipe insulation and inserting smaller styrofoam spacers between the individual sensors and the BHG3. That would create more positive thermal coupling between the thermocouple, embedded in a foil pad, and the borehole casing. This would improve coupling and eliminate the thermal effects of the black styrofoam. Thermal effects of the BHG3 could be reduced by enclosing it in a less bulky insulation package.

Thank you for the opportunity to work with you on this project. If you have questions or need additional information please contact me at your convenience.

Sincerely,

Zonge International, Inc.

Rowland B French

Rowland B. French, Ph.D., L.G.
Senior Geophysicist

Attachments: Figures 1-7: Borehole Temperature Logs

File: Zonge BH Temperature Rpt01.doc
NGA Project: 12130

REVISION: C-20-JULY-2012

FILE: VEW-04.grf

Zonge Project #: 12130

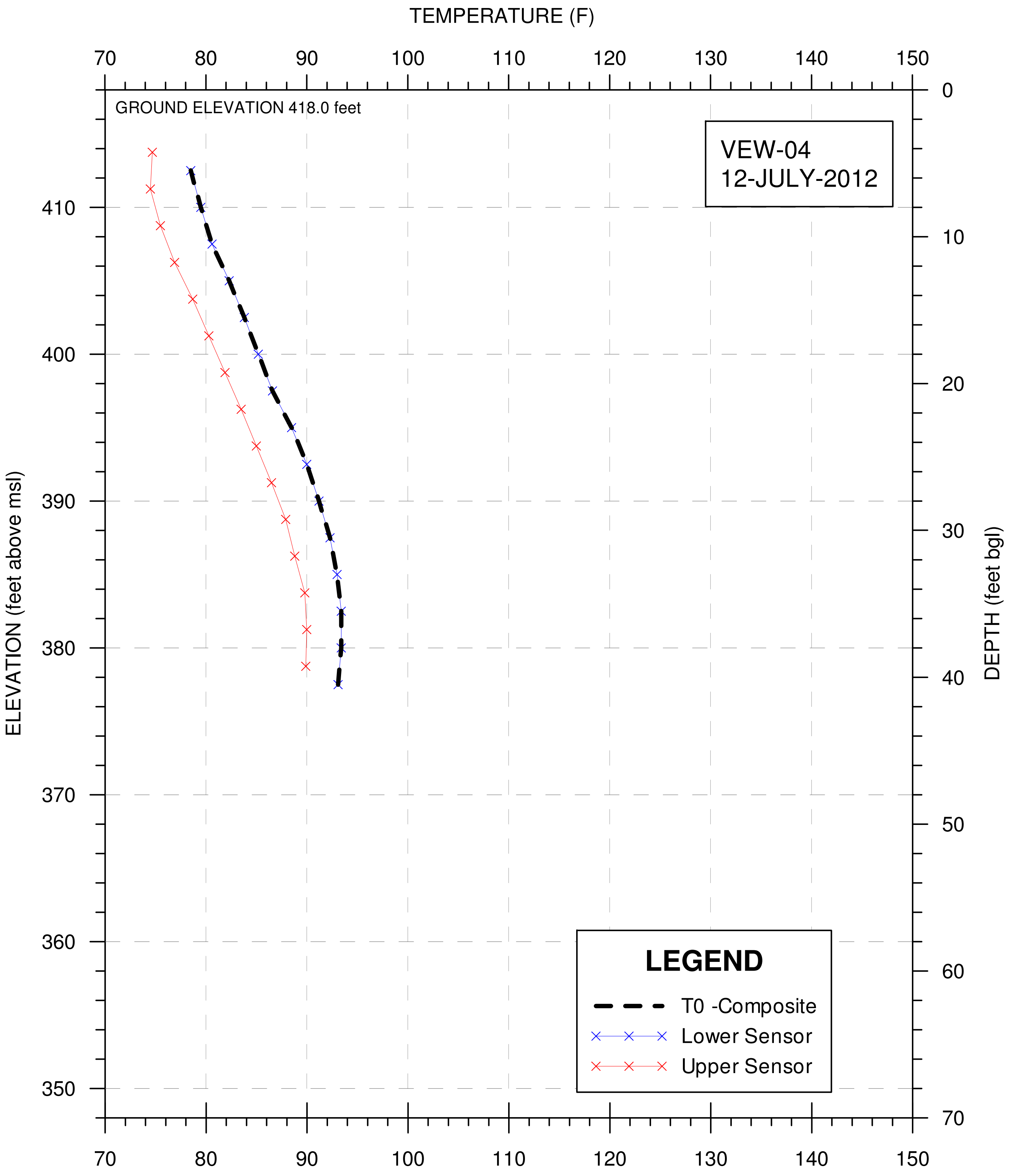


FIGURE 1

VEW-04

Borehole Temperature Log
Pasco Landfill
Pasco, Washington

Prepared by:
Zonge
TRUSTED GEOPHYSICS

REVISION: C-20-JULY-2012

FILE: VEW-05.grf

Zonge Project #: 12130

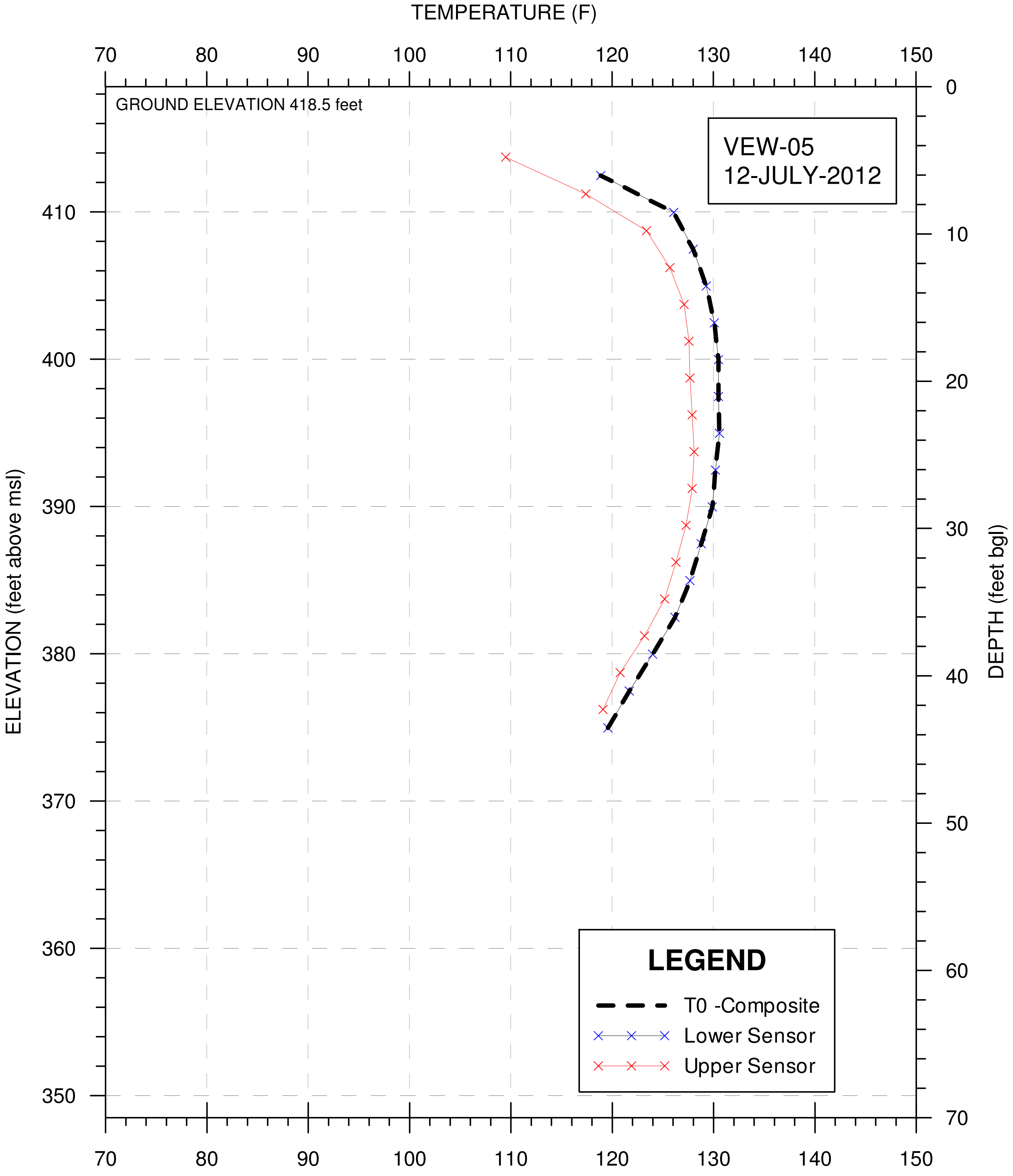


FIGURE 2

VEW-05

Borehole Temperature Log
Pasco Landfill
Pasco, Washington

Prepared by:
Zonge
TRUSTED GEOPHYSICS.

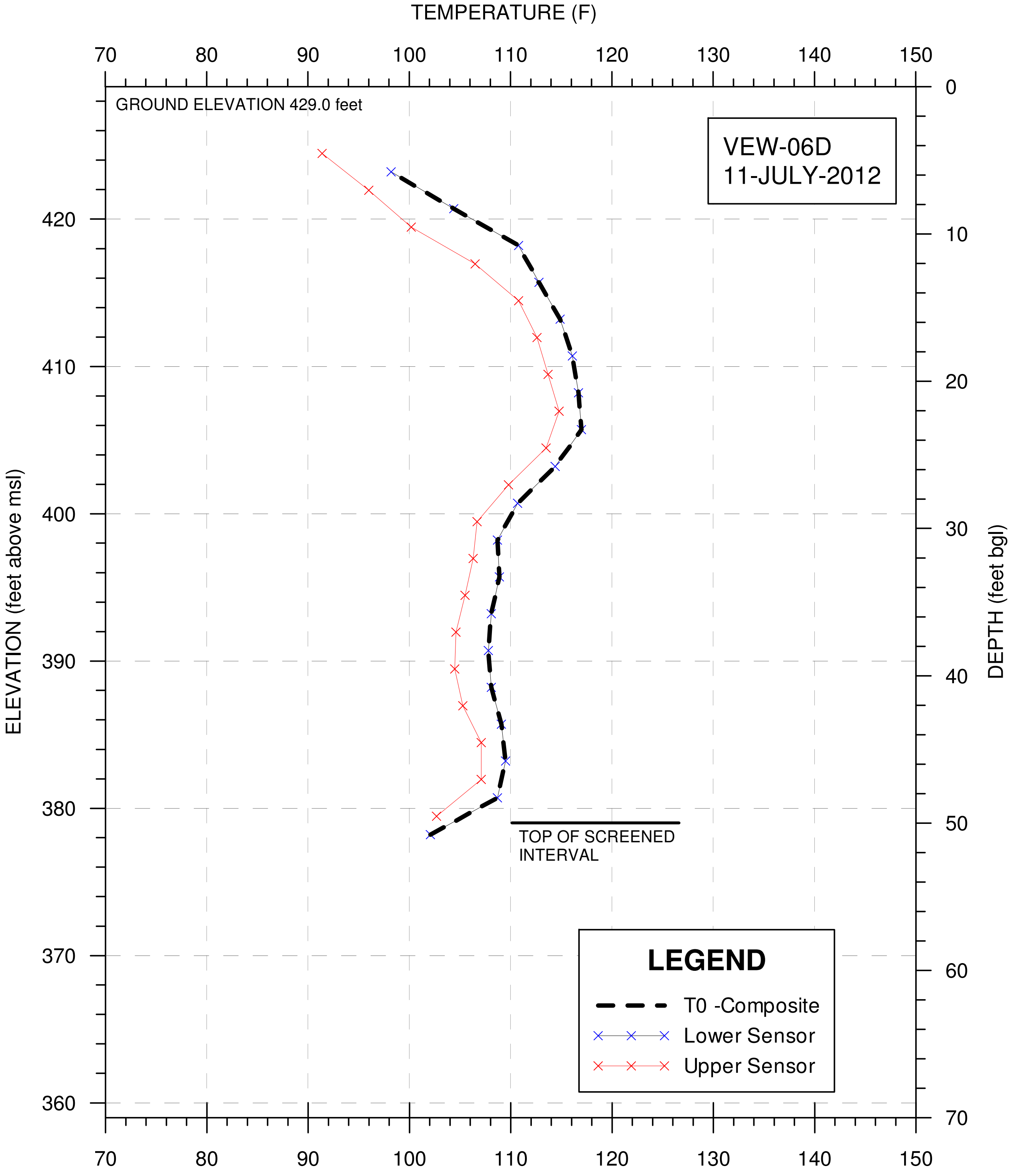


FIGURE 3

VEW-06D

Borehole Temperature Log
Pasco Landfill
Pasco, Washington

Prepared by:
Zonge
TRUSTED GEOPHYSICS

REVISION: C-20-JULY-2012

FILE: VEW-06D.grf

Zonge Project #: 12130

REVISION: C-20-JULY-2012

FILE: VEW-07D.grf

Zonge Project #: 12130

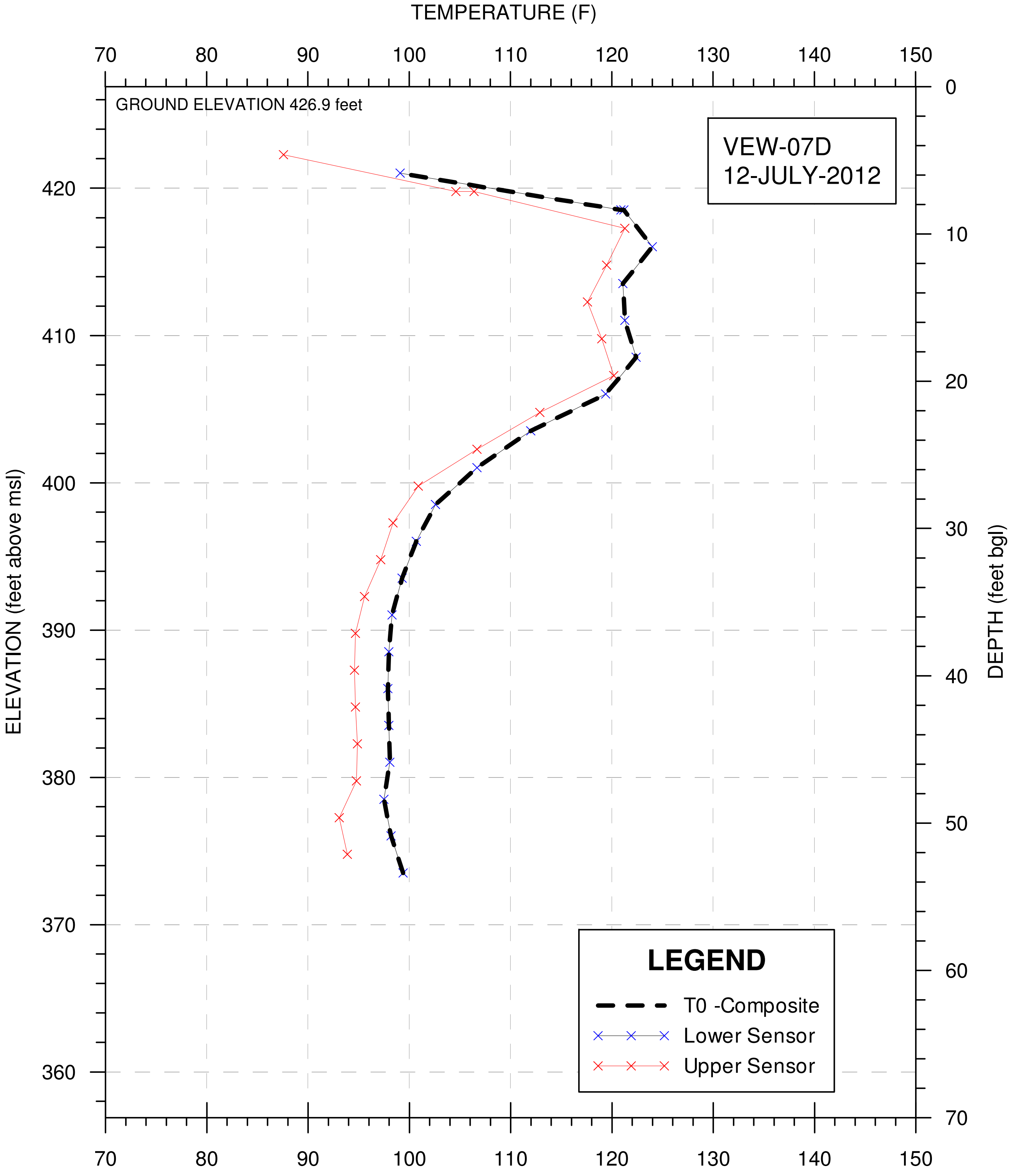


FIGURE 4

VEW-07D

Borehole Temperature Log
Pasco Landfill
Pasco, Washington

Prepared by:
Zonge
TRUSTED GEOPHYSICS.

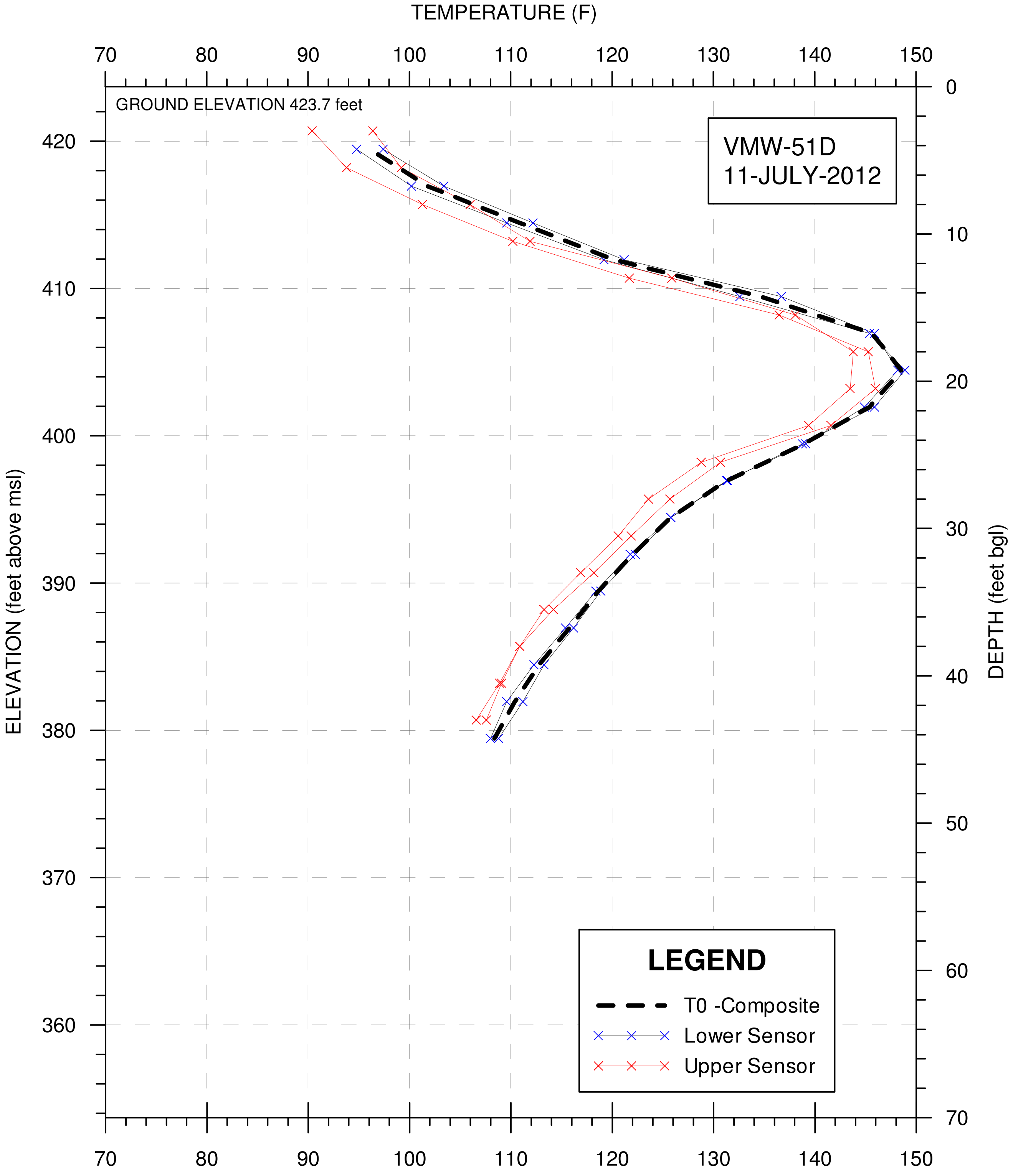


FIGURE 5

VMW-51D

Borehole Temperature Log
Pasco Landfill
Pasco, Washington

Prepared by:
Zonge
TRUSTED GEOPHYSICS.

REVISION: C-20-JULY-2012

FILE: MW-52S.grf

Zonge Project #: 12130

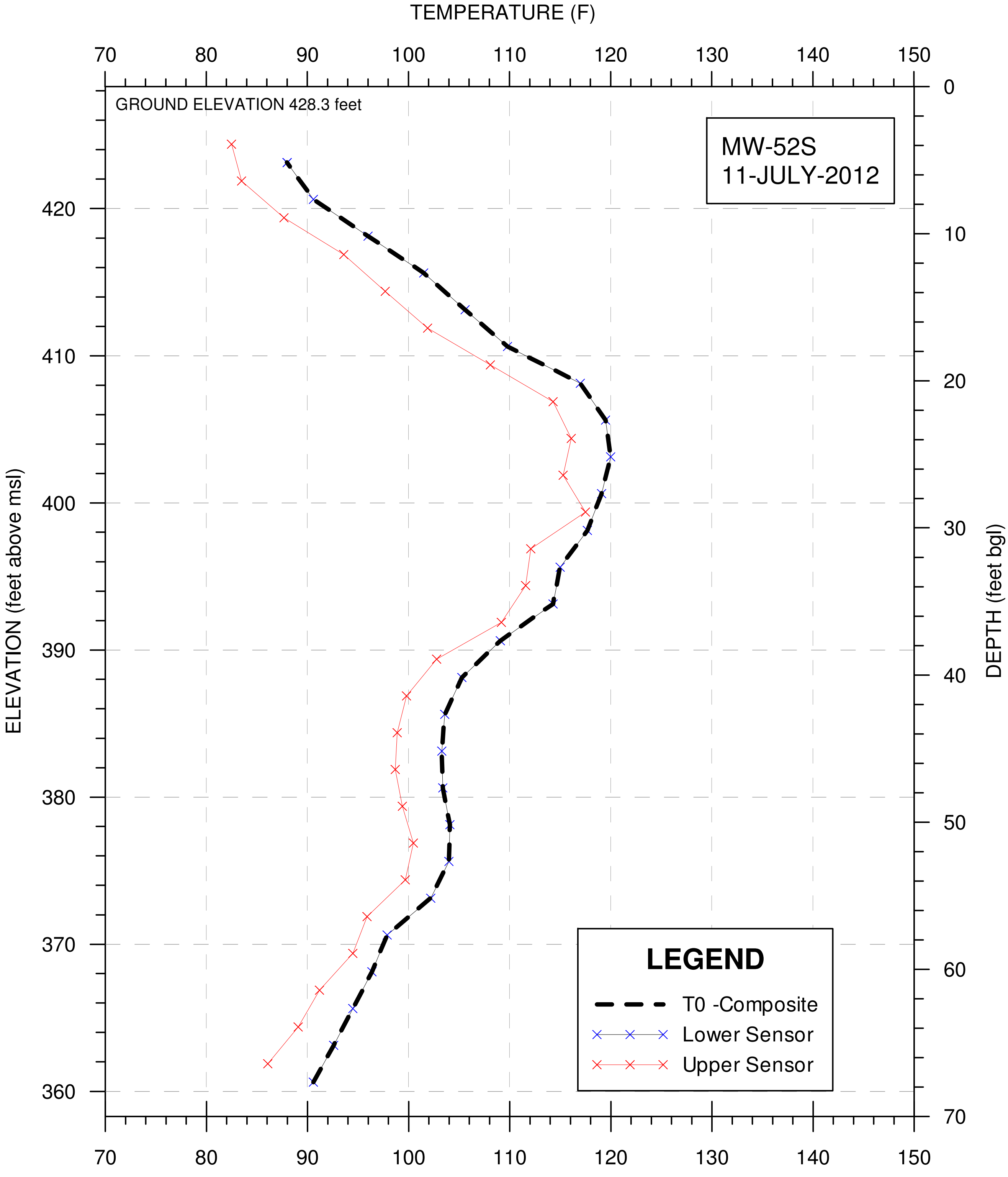


FIGURE 6

MW-52S

Borehole Temperature Log
Pasco Landfill
Pasco, Washington

Prepared by:
Zonge
TRUSTED GEOPHYSICS.

REVISION: C-20-JULY-2012

FILE: MW-53S.grf

Zonge Project #: 12130

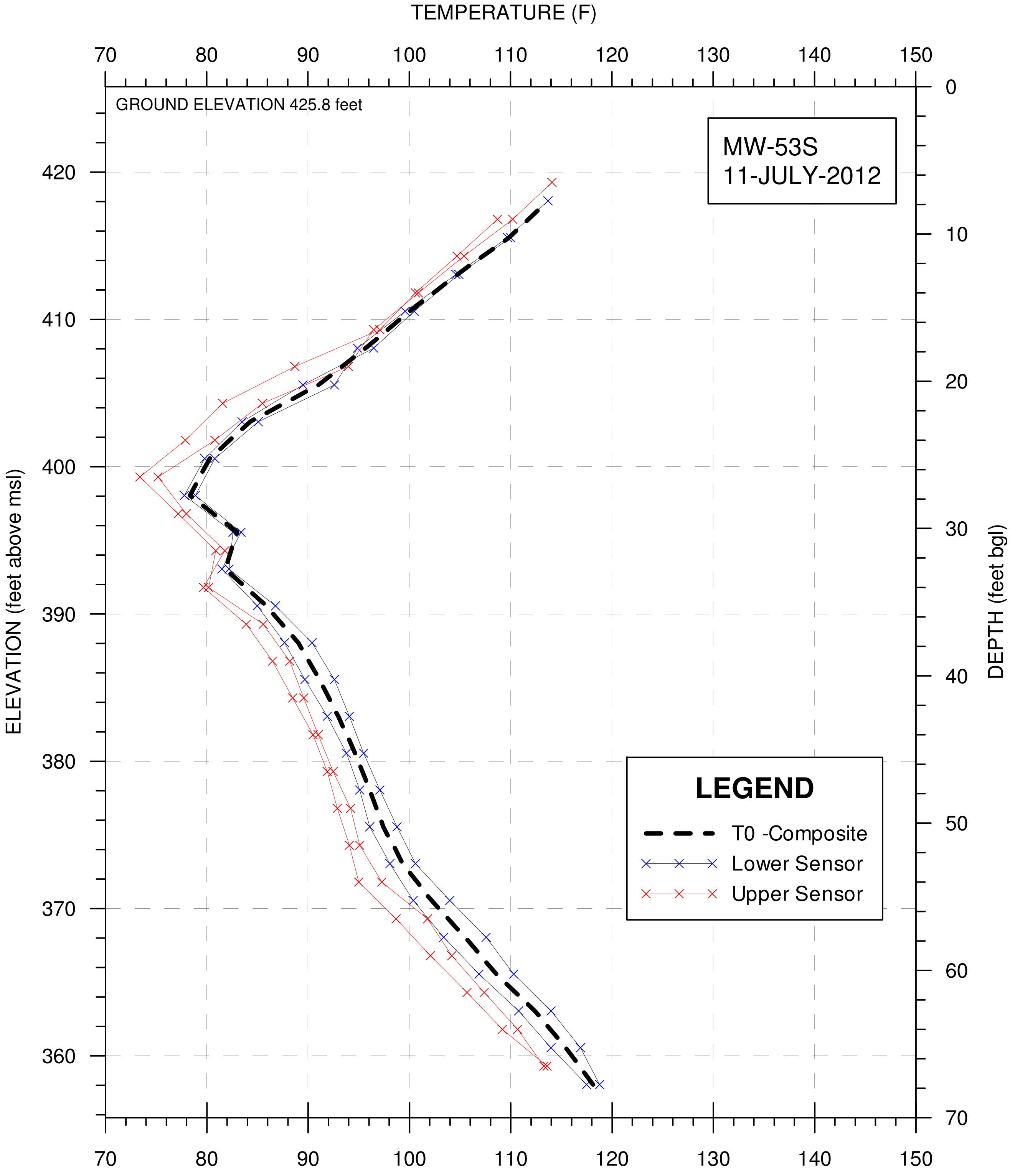


FIGURE 7

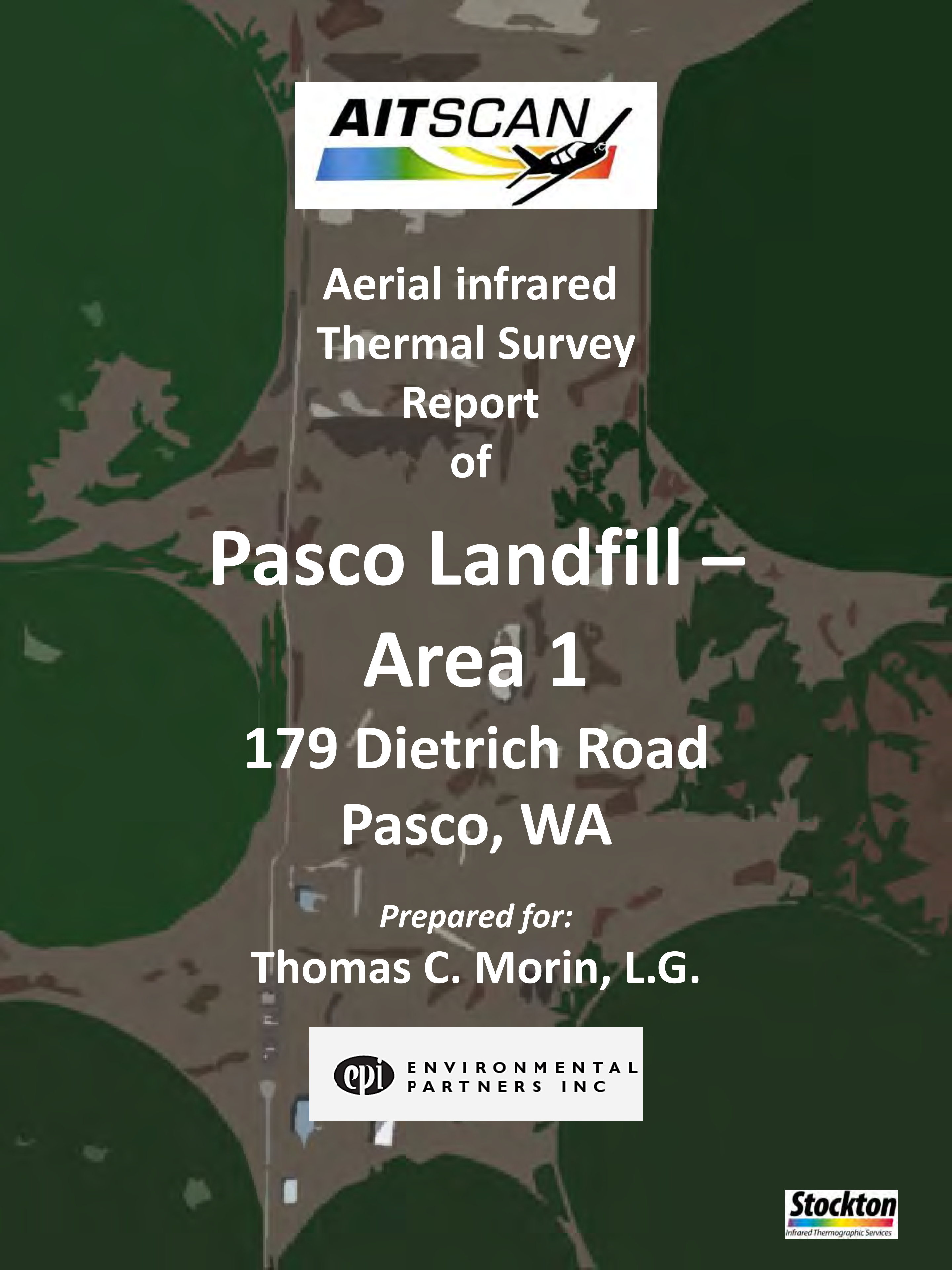
Prepared by:

Zonge
TRUSTED GEOPHYSICS.

MW-53S

Borehole Temperature Log
Pasco Landfill
Pasco, Washington

ATTACHMENT B
STOCKTON AERIAL THERMAL IMAGING REPORT



AITSCAN

Aerial infrared Thermal Survey Report of

Pasco Landfill – Area 1

179 Dietrich Road
Pasco, WA

Prepared for:

Thomas C. Morin, L.G.

epi ENVIRONMENTAL PARTNERS INC

Stockton
Infrared Thermographic Services

The World of Infrared

Stockton

Infrared Thermographic Services

June 8, 2012

Thomas C. Morin, L.G.
President/Principal
ENVIRONMENTAL PARTNERS, INC.
295 NE Gilman Boulevard, Suite 201
Issaquah, Washington 98027
425.395.0030 (direct)
206.954.6957 (cell)
thomm@epi-wa.com

epi ENVIRONMENTAL PARTNERS INC

**RE: Aerial Infrared Survey Report
Pasco Landfill – Area 1**

Dear Mr. Morin:

Pasco Landfill – Area 1 was the subject of an aerial infrared (IR) roof moisture survey on afternoon and night of Wednesday, June 27, 2012. The weather was dry with few clouds and low winds in the vicinity, providing good infrared imaging conditions.

This thermal survey of Pasco Landfill – Area 1 was intended to find heat differences on the surface of the landfill so that the extent of warm areas could be defined and any subsurface thermal events better managed. The imagery was digitally recorded and archived, so analysis could be carried out now, and also compared to future surveys. This will help build a thermal database on this landfill site.

Thermal infrared (IR) imagery in General

Infrared imagery shows heat. It is often in the form of a grayscale picture whose shades of gray indicate the differences in temperature and emissivity of objects in the image. Typically, objects in the image that look lighter are warmer and those that look darker are cooler. Bright white objects are the warmest in the images. Black objects are the coolest. Any object with a temperature above absolute zero (0 Kelvin or –273 degrees Celsius) emits infrared radiation. An infrared picture only shows objects which emit infrared wavelengths in the 3000-5000 or 8000-14000 nanometer range. Objects in visible light wavelengths of 400-700 nanometers are detected in the thermal imagery, but only because they also emit heat. An example of this would be a warm street light that can be seen in the IR imagery, not because it emits light…but because it emits heat. We recorded infrared imagery onto a computer hard drive and created digital image files. These image files were stitched together, creating mosaic images that were orthorectified. The images were then turned into the three file formats: Geo-TIFs Geo-JPEGs and KMZs.

Underground Thermal Events in General

Subsurface fires a.k.a., underground thermal events are almost always readily visible with infrared imaging, but it depends on the depth and temperature of the source of the heat, the density, thermal conductivity and specific heat capacity of the material above the source and the reflectivity of the surface. Warm areas are generally quite evident, having brighter white IR signatures that exceed the norm. We see only differences in surface temperatures...but very small differences are quite evident, since the IR cameras we use to perform these surveys can detect tenths of degrees differences in temperatures on the surface.

Underground Thermal Events in General (continued)

The heat energy from underground thermal events generally makes its way to the surface and can be seen in infrared imagery (shown below) as either; A) diffused, fuzzy, slightly warmer areas, and/or B) intense, bright spots in a group or by themselves.

A) Example of diffused heat

B) Example of intense spots

Analysis of Pasco Landfill – Area 1

Although there are no areas that are strongly indicative of an underground thermal event in Pasco Landfill – Area1, there are four "Anomaly Areas" contained within, which are shown and described on Pages 5 & 6.

Recommendations

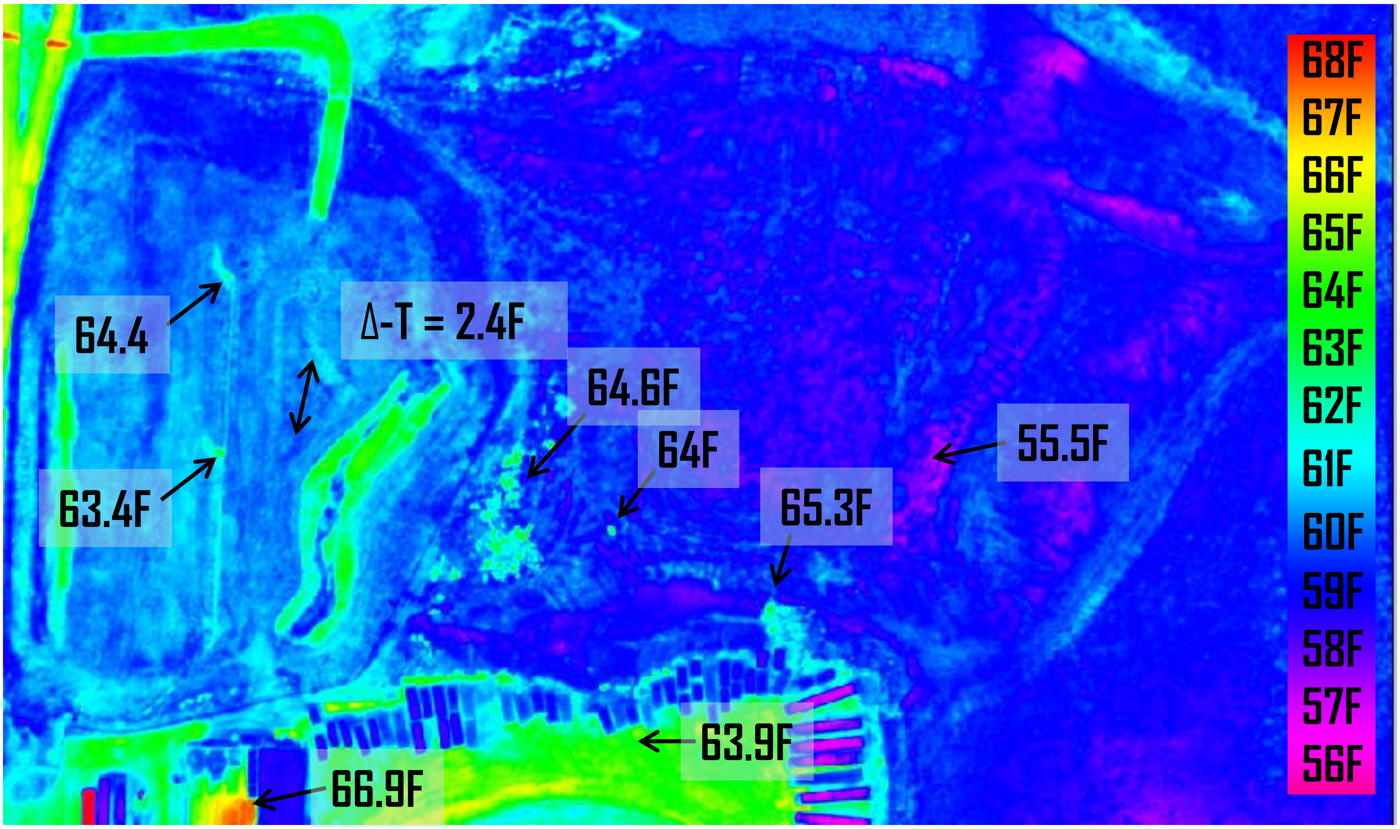
We recommend that the Pasco maintenance team carefully review the report. Then, with reference to the imagery and report provided, the Anomaly Areas should be physically located and given a thorough visual examination .

Please let me know if I can be of assistance to you by calling (800) 248-7226. We are looking forward to working with you on this important project.

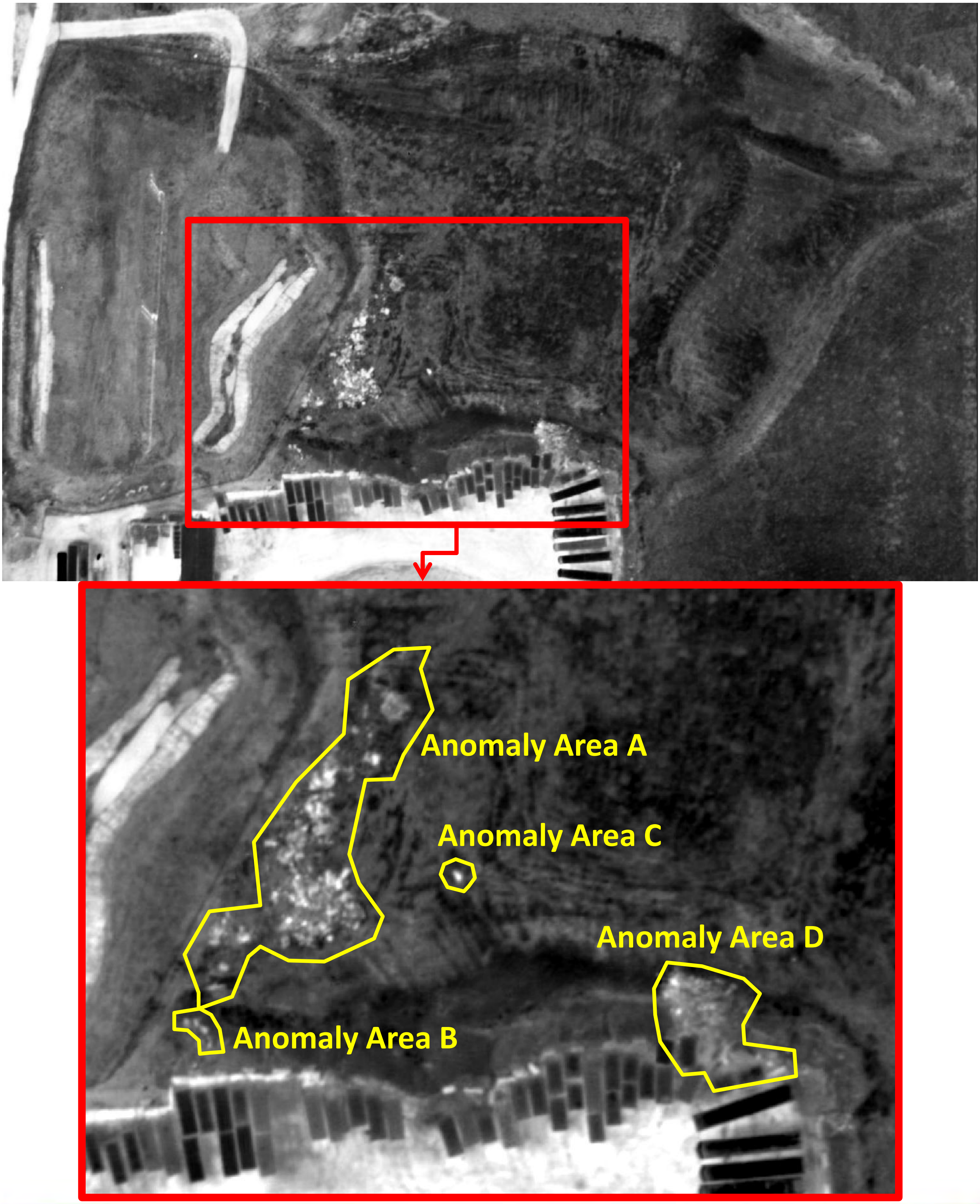
Sincerely yours,

Gregory R. Stockton
Certified Infrared Thermographer #3583

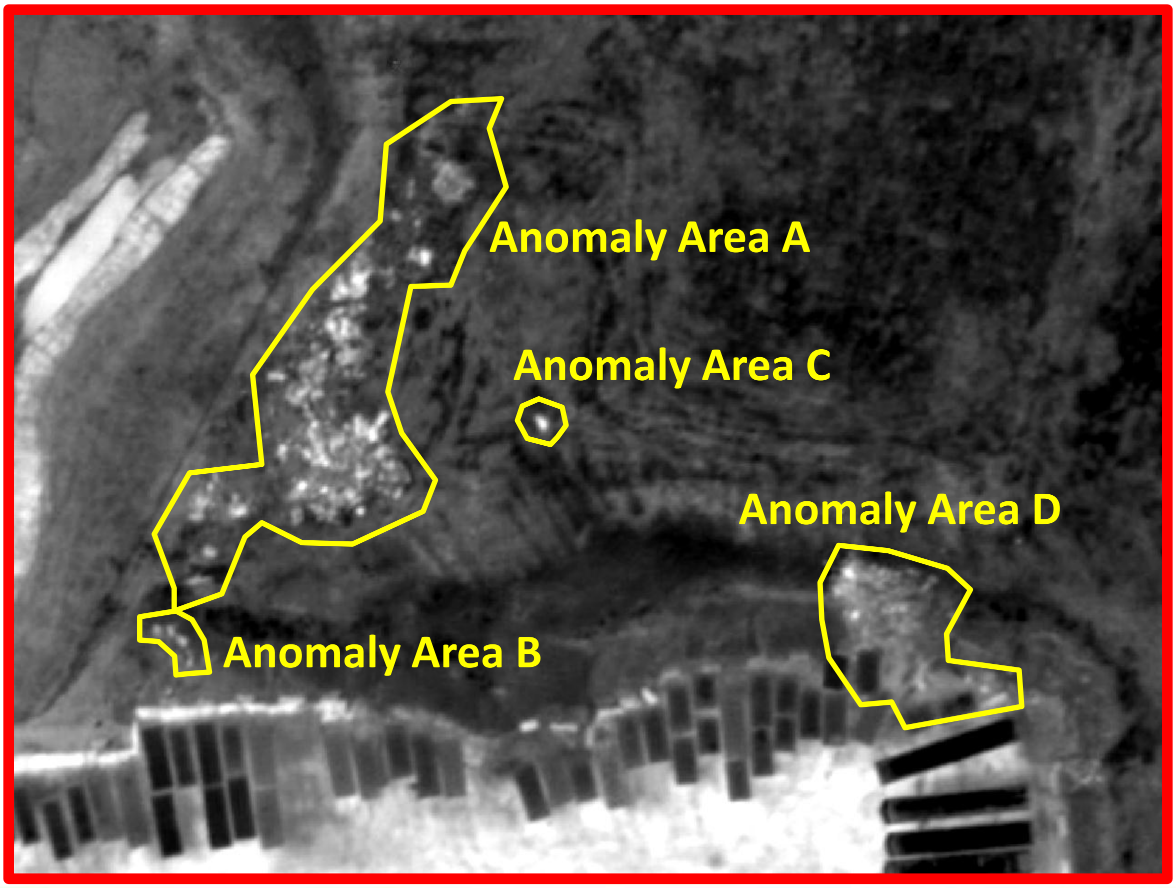
Infrared Greyscale Image, Normal Contrast


64.4
Δ-T = 2.4F
64.6F
64F
55.5F
63.4F
65.3F
63.9F
66.9F
68F
67F
66F
65F
64F
63F
62F
61F
60F
59F
58F
57F
56F

Infrared Greyscale Image, High Contrast



Anomaly Areas
A – Anomaly Area, probably construction debris (see photo below)
B – Anomaly Area, probably construction debris (see photo below)
C – Anomaly Area within the construction debris piles
D – Anomaly Area near storage area



ATTACHMENT C
METHANE ISOTOPIC ANALYSIS

421 SW Sixth Avenue, Suite 750
Portland, Oregon 97204
Phone 503.688.5057
www.anchorqea.com

MEMORANDUM

To:	Charles Gruenenfelder, Washington Department of Ecology	**Date:**	October 29, 2012
From:	Jessica Goin, Ph.D., and Dimitri Vlassopoulos, Ph.D., Anchor QEA		
Cc:	Bob Isenberg, P.E., CPG, and John Richards, P.E., SCS Engineers Thom Morin, L.G., Environmental Partners		
Re:	Methane Isotopic Analysis from SVE Extraction Wells VEW-06I and VEW-07I Addendum to the Zone A Heating Evaluation, Pasco Sanitary Landfill Site		

This addendum to the September 14, 2012, Zone A Heating Evaluation, Pasco Sanitary Landfill Site Memorandum (SCS Engineers, Anchor QEA, and Environmental Partners 2012) is provided to address methane isotope data from SVE extraction wells VEW-06I and VEW-07I received following submittal of the original memorandum. The original memorandum was revised to address comments from the Washington Department of Ecology. The findings presented in this memorandum were incorporated in the revised memorandum.

BACKGROUND

Gas samples from VEW-06I, VEW-07I, and VMW-51I collected on 6/25/12 and 7/9/12 were submitted to Isotech Laboratories for analysis of the stable isotopes of methane (CH_4) and carbon dioxide (CO_2). Replicate samples were submitted to the SoMAS Laboratory for carbon monoxide (CO) stable isotope analysis. Isotech Laboratories reported the carbon and hydrogen isotopic fractionation of CH_4 for the two samples from VWM-51I; however, they were unable to perform the isotopic analysis for VEW-06I and VEW-07I, as the CH_4 concentrations were below the threshold level required by that laboratory to perform the isotopic analysis. The SoMAS Laboratory indicated that they could provide analysis of the carbon isotope ratio of CH_4 with an in-line method that has a lower concentration threshold. The samples submitted to the SoMAS Laboratory for CO isotopic analysis were submitted in duplicate as a precaution against sample loss, so they had samples from VEW-06I, VEW-07I, and VMW-51I to perform a cross-laboratory duplicate analysis. The SoMAS Laboratory does not analyze hydrogen isotopes.

Stable isotope data are reported as the abundance ratio of the trace isotope to the more abundant light isotope relative to the same ratio in an international reference standard (USEPA 2008; ITRC 2012). The ratio of the heavy and light isotope in the sample, relative to the ratio of the heavy and light isotope in the standard, is reported as the delta (δ) of the isotope in parts per mil. The two laboratories performing isotopic analysis both reported the carbon-13/carbon-12 isotope fractionation ($\delta^{13}C$) relative to the Vienna PeeDee Belemnite (VPDB) standard. The deuterium/hydrogen fractionation ($\delta^{2}H$) of CH_4 was reported relative to the VSMOW standard.

RESULTS

The $\delta^{13}C$ and $\delta^{2}H$ of CH_4 was determined by Isotech Laboratories for two samples from VMW-51I. The SoMAS Laboratory produced $\delta^{13}C$ of CH_4 results for two samples from VEW-06I, one sample from VEW-07I, and one sample from VMW-51I. The results of the CH_4 isotope analysis, including for the previously reported VMW-51I samples, is summarized in Table 1.

Table 1
Methane isotope fractionation

Sample Location	Sample Date	$\delta^{13}C$ per mil	$\delta^{2}H$ per mil	$\delta^{13}C$ Error per mil	Laboratory
VEW-06I	6/25/2012	-107.5		1.9	SoMAS Laboratory
	7/9/2012	-91.3		2.4	SoMAS Laboratory
VEW-07I	7/9/2012	-96.2		3.0	SoMAS Laboratory
VMW-51I	6/25/2012	-76.5	-353.8	0.1	[1]Isotech Laboratories
	7/9/2012	-74.4	-367.2	0.1	[1]Isotech Laboratories
		-73.0		1.8	SoMAS Laboratory

Note:

1. Previously reported in the September 14 memorandum.

Some precision was lost on the fractionation value due to the lower CH_4 concentrations; however, even with the reported measurement error on the $\delta^{13}C$ value (up to 3 per mil), the values for VEW-06I and VEW-07I are distinct from those in VMW-51I. The cross-laboratory duplicate samples for VMW-51I (7/9/20120) were in excellent agreement for δ^{13}C of CH_4.

DISCUSSION

The δ^{13}C of CH_4 in gas samples from VEW-06I, VEW-07I, and VMW-51I is inconsistent with combustion (Yamada et al. 2006; Ferretti et al. 2005). The highly depleted δ^{13}C signatures (high negative values) indicates a bacterial source of CH_4 in VMW-51I and in Zone A (Bogner et al. 1996; Whiticar et al. 1986). Figure 1 is a cross-plot of δ^{13}C and δ^{2}H for CH_4 of the VMW-51I data, with the δ^{13}C of CH_4 for the inter-laboratory duplicate sample from VMW-51I. Results for VEW-06I and VEW-07I are also shown on Figure 1; since δ^{2}H was not determined, these results are shown as a range with respect to δ^{2}H. The isotopic signature of CH_4 in VMW-51I, VEW-06I, and VEW-07I is consistent with a bacterial source of CH_4 and is not consistent with combustion (Bogner et al. 1996; Whiticar et al. 1986; Whiticar 1999).

The carbon isotope fractionation of samples from VEW-06I and VEW-07I is especially depleted, as compared to fractionation in VMW-51I samples, which is indicative of a distinct source of CH_4. The decreasing CH_4 concentration fromVMW-51I to VEW-06I to VEW-07I, corresponding to increasing oxygen levels, is consistent with bacterial consumption of CH_4. However, if the source of CH_4 in VEW-06I and VEW-07I was residual CH_4 from a source near VMW-51, these samples would have CH_4 that is enriched in ^{13}C (e.g., Coleman et al. 1981; Whiticar 1999; Valentine et al. 2001).

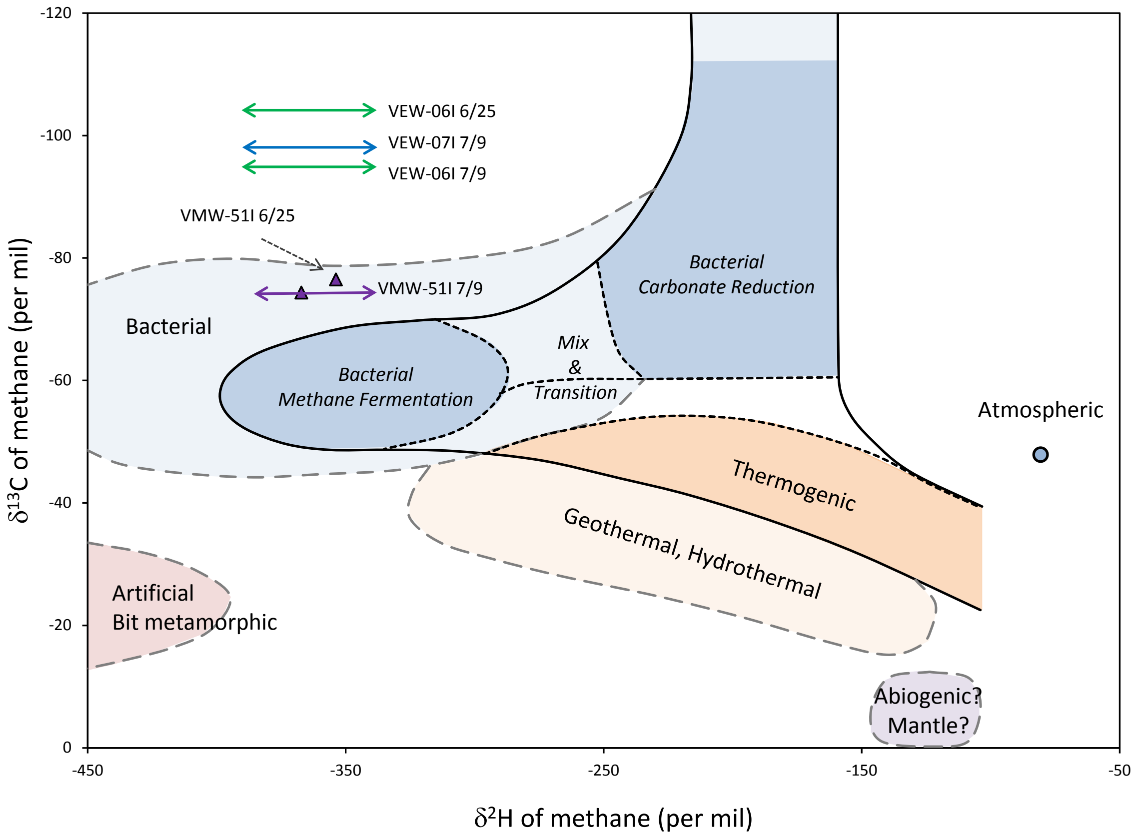


Figure 1

Isotopic Signature of CH_4 from VMW-51I, VEW-06I, and VEW-07I (carbon fractionation only). The approximate fields for fractionation by various processes are outlined after Whiticar 1999.

The source of bacterial CH_4 within Zone A could be aerobic or anaerobic biodegradation of the organic compounds present in Zone A, including aromatic compounds (toluene), ketones (acetone), and chlorinated alkanes. Of these potential CH_4 sources, only two would explain the highly depleted $\delta^{13}C$ signature – either complex carbon cycling between methanogens and methanotrophs, or biodegradation of acetone.

The $\delta^{13}C$ of CH_4 with as great, or greater, depletion of the heavy isotope have been reported in environments with complex cycling of CO_2 and CH_4. Complex cycling between methanogenic and methanotrophic bacterial communities, where bacterial CH_4 is consumed by methanotrophs that generate CO_2, some of which is in turn converted back to CH_4 by methanogens, will generate $\delta^{13}C$ depletion in the -100 per mil range (e.g., Borowski et al.

1997; Pancost et al. 2000). However, this complex CH_4 cycling has only been identified in select carbon limited environments in deep ocean sediments, where methanotrophs and methanogens are in close spatial proximity near a boundary in the oxidation-reduction potential and is unlikely to occur within the landfill.

A more likely explanation is that the CH_4 in VEW-06I and VEW-07I is generated as a byproduct of ketone degradation, which could explain the highly depleted $\delta^{13}C$ of CH_4. Acetone is degraded under anaerobic conditions to CH_4 and CO_2 (Sanin et al. 2000). Acetone is also biodegraded under aerobic conditions, with CH_4 and CO generated as intermediates during degradation (Stefan and Bolton 1999).

Biodegradation of acetone would account for the highly depleted $\delta^{13}C$ of CH_4. Several lines of evidence suggest that CH_4 generated during acetone biodegradation would have a highly depleted $\delta^{13}C$ signature. During biological production of the ketone 3-hydroxybutanone, the ^{13}C isotope is selectively assigned to the carbonyl carbon, leading to an enriched carboxyl group as compared to the methyl group (Rinaldi et al. 1974a). The production of acetone is primarily by the Hock Process, which involves a low temperature re-arrangement of the functional groups that become acetone (Yadav and Asthana 2003), and this may result in a similar intramolecular fractionation in acetone. Further, degradation of acetone and other ketones involves the formation of acetate as an early intermediate in the degradation process (Stefan and Bolton 1999; Platen and Schink 1987; Platen et al. 1994; Gao et al. 2010). Biological production of acetate (acetic acid) also leads to intra-molecular isotopic fractionation, with the heavier carbon isotope selectively assigned to the carboxyl group (Rinaldi et al. 1974b; Meinschein et al. 1974), which would increase the $\delta^{13}C$ depletion of the methyl group. Finally, a study of isotopic fractionation during methanogenesis involving cleavage of a methyl group from the substrate demonstrated a highly depleted $\delta^{13}C$ for the generated CH_4, with enrichment factors of -72 to -83 per mil for the methane as compared to the substrate (Penger et al. 2012). These several lines of evidence indicate that the highly depleted $\delta^{13}C$ for CH_4 in VEW-06I and VEW-07I likely reflect methane generated by bacterial cleavage of ketone methyl groups.

As discussed in the Zone A Heating Memorandum, the isotopic signature of CO in VEW-06I is consistent with CO production from degradation of acetone (Sternberg and DeNiro 1983), suggesting that the CO present in VEW-06I is the result of acetone degradation. The isotopic signature of CO in VEW-07I is between that of acetone degradation and the more typical signature for bacterial CH_4 oxidation observed in VMW-51I, and the concentration of CO is higher in VEW-07I, suggesting that CO from both acetone degradation and methane oxidation are present in VEW-07I.

SUMMARY

The $\delta^{13}C$ of CH_4 from VMW-51I, VEW-06I, and VEW-07I is inconsistent with combustion and is indicative of a bacterial source of CH_4. Additionally, the depletion of CH_4 $\delta^{13}C$ in VEW-06I/VEW-07I samples, as compared to VMW-51I samples, indicates a distinct source of bacterial CH_4 within Zone A. This source is likely bacterial ketone degradation in Zone A.

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ATTACHMENT D
DATA TABLES

Table 1
Field Measurements
Zone A Heating Evaluation
Pasco Landfill, Pasco, WA

PERIOD: 5/14 - 7/16//2012

Well	Date	Skid Vacuum (in. H_2O)	Skid LEL (%)	Well Head Airflow (cfm)	Dilution Airflow (cfm)	Total Airflow (scfm)	Well Head Vacuum (in. H_2O)	Well Head Temp (F)	Well Head CO2 (%)	Well Head O2 (%)	Well Bal Gas (%)	Well Head PID	Well Head LEL (%)	Field CH4 (%)	Field CO (ppmV)	Field NO	Field NO2
VEW-06S	5/14/12	-53	15	58	0	58	-33.5	92	3.1	15.6	81.2	787	21	0	2	0	3.7
	5/15/12	-53	15	57	0	57	-34.0	92	4.6	15.3	80.1	1,015	34	0	0	0	0
	5/16/12	-53	11	62	0	62	-34.2	92	4.7	15.6	80.0	1,204	10	0	0	0	3.4
	5/17/12	-100	9	147	0	147	-81	90	5.3	14.7	79.9	1,406	14	0	0	0	7.9
	5/21/12	-102	15	150	0	150	-82.0	90	1.0	19.0	79.8	1,817	12	0	0	0	4.3
	5/23/12	-102	11	152	0	152	-83.0	90	4.5	15.4	79.5	1,976	14	0	0	0	0
	5/24/12	-103	11	150	0	150	-82	90	4.7	13.9	80.6	3,226	14	0	2	0	0
	5/25/12	-99	13	148	0	148	-80	92	3.6	15.0	80.3	1,594	18	0	0	--	--
	5/29/12	-100	9	141	0	141	-81	93	4.6	14.1	80.8	1,524	10	--	--	--	--
	5/31/12	-100	8	141	0	141	-81	94	4.3	14.3	80.3	7,566	8	--	--	--	--
	6/1/12	-100	9	140	0	140	-81	95	4.4	14.2	80.6	2,894	12	--	--	--	--
	6/4/12	-101	5	137	0	137	-80	91	4.6	14.4	80.4	1,953	9	--	--	--	--
	6/6/12	-102	3	136	0	136	-82	90	4.7	14.2	80.4	1,735	12	--	--	--	--
	6/8/12	-103	4	137	0	137	-82	96	4.3	14.4	80.7	1,525	12	--	--	--	--
	6/11/12	-99	4	140	0	140	-81	94	3.6	14.7	80.9	1,113	14	--	--	--	--
	6/13/12	-100	5	138	0	138	-82	98	3.8	14.5	80.9	1,633	11	--	--	--	--
	6/15/12	-100	6	137	0	137	-81	98	4.6	14.5	80.2	1,315	13	--	--	--	--
	6/18/12	-101	6	136	0	136	-81	98	4.7	14.2	80.4	1,920	12	--	--	--	--
	6/20/12	-99	21	139	0	139	-81	100	5.5	13.7	80.1	1,704	10	--	--	--	--
	6/22/12	-99	26	135	0	135	-80	99	5.3	13.2	80.5	1,694	18	--	--	--	--
	6/25/12	-101	21	139	0	139	-81	100	4.7	15.1	79.6	1,687	11	--	--	--	--
	6/27/12	-102	19	138	0	138	-83	100	4.7	15.3	79.3	1,796	10	--	--	--	--
	6/29/12	-102	21	144	0	144	-82	100	4.7	15.3	79.3	1,976	12	--	--	--	--
	7/2/12	-141	21	136	0	136	-81	101	4.4	14.7	80.1	2,010	13	--	--	--	--
	7/5/12	-102	19	138	0	138	-81	102	4.2	14.9	80.1	1,299	19	--	--	--	--
	7/9/12	-101	19	143	0	143	-81	102	4.6	15.1	79.6	1,707	13	--	--	--	--
	7/11/12	-101	19	142	0	142	-81	102	4.7	14.7	79.9	1,568	13	--	--	--	--
	7/13/12	-97	19	143	0	143	-81	103	4.7	15.3	79.3	2,980	13	--	--	--	--
VEW-06I	5/14/12	-53	15	44	71	115	-10.9	122	8.3	5.8	85.6	4,141	100+	0	517	0	0
	5/15/12	-53	15	45	72	117	-10.9	123	10.6	5.4	83.9	4,769	100+	0	396	0	0
	5/16/12	-53	11	38	69	107	-11.3	122	10.9	5.7	83.1	9,999	100+	0	373	0	1.5
	5/17/12	-100	9	~5	0	~5	-3.1	116	12.1	1.7	86.0	4,781	100+	0	307	0	4.8
	5/21/12	-102	15	~5	0	~5	-2.9	101	12.1	1.6	86.0	8,379	100+	0	302	0	2
	5/23/12	-102	11	~5	0	~5	-3.3	107	13.8	1.4	78.6	9,429	100+	0	233	0	0
	5/24/12	-103	11	~5	0	~5	-2.8	108	12.7	2.1	75.2	9,999	100+	0	331	0	0
	5/25/12	-99	13	~5	0	~5	-3.9	115	11.7	3.9	74.5	4,487	100+	0	376	--	--
	5/29/12	-100	9	~5	0	~5	-3.7	116	12.7	2.3	74.3	4,866	100+	--	--	--	--
	5/31/12	-100	8	~5	0	~5	-3.7	116	12.8	2.0	76.5	9,999	100+	--	--	--	--
	6/1/12	-100	9	~5	0	~5	-3.4	118	13.0	1.8	73.4	9,999	100+	--	--	--	--
	6/4/12	-101	5	~5	0	~5	-3.5	114	13.7	1.1	70.7	4,584	100+	--	--	--	--
	6/6/12	-102	3	~5	0	~5	-3.4	94	13.7	1.9	77.4	1,748	100+	--	--	--	--
	6/8/12	-103	4	~5	0	~5	-3.1	104	12.9	1.6	77.9	4,692	100+	--	--	--	--
	6/11/12	-99	4	~5	0	~5	-2.9	116	12.7	1.3	75.7	1,151	100+	--	--	--	--
	6/13/12	-100	5	~5	0	~5	-3.1	110	13.2	1.1	76.3	1,644	100+	--	--	--	--
	6/15/12	-100	6	~5	0	~5	-3.3	115	12.8	3.0	75.9	1,245	100+	--	--	--	--
	6/18/12	-101	6	~5	0	~5	-3.2	122	14.0	0.7	74.1	1,767	100+	--	--	--	--
	6/20/12	-99	21	~5	0	~5	-2.8	122	14.9	0.3	73.5	1,710	100+	--	--	--	--
	6/22/12	-99	26	~5	0	~5	-2.9	121	13.9	0.9	71.5	1,303	100+	--	--	--	--
	6/25/12	-101	21	~5	0	~5	-3.0	122	14.1	1.3	72.8	1,392	100+	--	--	--	--
	6/27/12	-102	19	~5	0	~5	-3.1	124	14.2	1.5	73.8	1,543	100+	--	--	--	--
	6/29/12	-102	21	~5	0	~5	-3.1	122	14.2	1.4	75.2	1,613	100+	--	--	--	--
	7/2/12	-141	21	~5	0	~5	-2.8	124	13.1	2.3	68.4	1,724	100+	--	--	--	--
	7/5/12	-102	19	~5	0	~5	-3.0	124	13.1	1.8	68.7	1,485	100+	--	--	--	--
	7/9/12	-101	19	~5	0	~5	-3.2	121	14.1	0.8	71.2	1,309	100+	--	--	--	--
	7/11/12	-101	19	~5	0	~5	-2.9	124	14.3	1.0	71.7	1,279	100+	--	--	--	--
	7/13/12	-97	19	~5	0	~5	-3.2	122	13.8	2.5	74.3	9,999	100+	--	--	--	--

PERIOD: 5/14 - 7/16//2012

Table 1
Field Measurements
Zone A Heating Evaluation
Pasco Landfill, Pasco, WA

Well	Date	Skid Vacuum (in. H_2O)	Skid LEL (%)	Well Head Airflow (cfm)	Dilution Airflow (cfm)	Total Airflow (scfm)	Well Head Vacuum (in. H_2O)	Well Head Temp (F)	Well Head CO2 (%)	Well Head O2 (%)	Well Bal Gas (%)	Well Head PID	Well Head LEL (%)	Field CH4 (%)	Field CO (ppmV)	Field NO	Field NO2
VEW-06D	5/14/12	-4	21	56	0	56	-2.3	92	2.4	14.1	82.7	1,019	22	0	3	0	9.3
	5/15/12	-5	23	51	0	51	-2.8	92	4.0	13.9	82.1	1,233	15	0	0	0	0
	5/16/12	-4	23	51	0	51	-3.1	91	4.4	14.1	81.3	1,446	15	0	0	0	3.7
	5/17/12	-10	15	102	0	102	-5.6	91	4.1	13.9	82.1	1,379	13	0	0	0	7.9
	5/21/12	-10	12	104	0	104	-5.7	90	3.8	14.2	82.1	1,725	11	0	0	0	3.6
	5/23/12	-10	10	106	0	106	-6.1	88	5.5	13.8	79.8	2,176	11	0	0	0	0
	5/24/12	-10	9	104	0	104	-5.1	90	5.3	13.6	80.3	1,759	13	0	0	0	0
	5/25/12	-10	10	104	0	104	-5.6	90	5.0	13.8	80.5	1,322	12	0	2	--	--
	5/29/12	-10	8	99	0	99	-5.6	90	5.2	13.7	80.5	1,308	11	--	--	--	--
	5/31/12	-10	5	96	0	96	-5.5	91	5.2	13.7	80.4	1,805	12	--	--	--	--
	6/1/12	-9	7	96	0	96	-5.4	89	5.4	13.7	80.1	1,797	14	--	--	--	--
	6/4/12	-9	5	99	0	99	-5.0	92	5.4	13.7	80.2	1,447	9	--	--	--	--
	6/6/12	-10	5	159	0	159	-7.0	89	5.5	13.7	80.2	1,444	14	--	--	--	--
	6/8/12	-11	8	151	0	151	-6.0	90	5.1	13.7	80.5	1,334	12	--	--	--	--
	6/11/12	-11	5	109	0	109	-5.5	92	5.1	13.7	80.3	889	14	--	--	--	--
	6/13/12	-9	19	99	0	99	-5.8	91	5.2	13.7	80.4	1,215	11	--	--	--	--
	6/15/12	-11	23	99	0	99	-6.5	91	5.1	13.9	80.0	954	15	--	--	--	--
	6/18/12	-11	8	104	0	104	-6.3	90	5.4	13.8	80.0	1,243	15	--	--	--	--
	6/20/12	-11	6	108	0	108	-5.9	92	5.1	15.0	79.1	1,263	15	--	--	--	--
	6/22/12	-11	23	104	0	104	-6.0	92	5.4	14.2	79.3	941	20	--	--	--	--
	6/25/12	-11	23	106	0	106	-6.0	92	5.3	14.7	79.2	1,081	15	--	--	--	--
	6/27/12	-10	23	111	0	111	-5.8	92	5.2	14.8	79.2	1,143	14	--	--	--	--
	6/29/12	-9	21	93	0	93	-6.0	89	5.2	14.9	79.2	1,273	13	--	--	--	--
	7/2/12	-7	26	85	0	85	-4.5	92	4.9	14.5	79.8	1,425	13	--	--	--	--
	7/5/12	-9	23	85	0	85	-5.5	94	4.8	14.5	80.1	912	10	--	--	--	--
	7/9/12	-9	21	103	0	103	-6.7	90	5.0	14.7	79.4	1,048	14	--	--	--	--
	7/11/12	--	21	0	0	0	-0.5	--	--	--	--	--	14	--	--	--	--
	7/13/12	-10	19	98	0	98	-6.1	93	5.3	14.4	76.6	2,027	12	--	--	--	--
VEW-07S	5/14/12	-47	26	105	0	105	-30.0	88	2.8	14.3	82.7	2,221	31	0	17	0	0
	5/15/12	-46	19	107	0	107	-30.0	87	3.4	14.5	81.9	3,818	24	0	13	0	1.6
	5/16/12	-46	17	111	0	111	-30.2	88	3.7	14.6	81.5	4,858	36	0	8	0	2.2
	5/17/12	-78	13	167	0	167	-57	87	2.4	15.4	82.2	4,686	30	0	23	0	9.5
	5/21/12	-73	23	167	0	167	-5.7	89	0.8	17.4	81.7	6,529	28	0	29	0	4.8
	5/23/12	-74	21	168	0	168	-57.0	88	4.5	14.7	79.5	5,180	28	0	17	0	0
	5/24/12	-74	21	159	0	159	-56	90	3.2	15.8	79.2	4,475	35	0	29	0	0
	5/25/12	-73	21	161	0	161	-56	90	2.6	16.7	79.1	3,916	31	0	27	--	--
	5/29/12	-72	21	166	0	166	-56	92	3.0	16.0	79.4	4,223	24	--	--	--	--
	5/31/12	-73	17	166	0	166	-56	92	4.2	14.2	79.1	6,180	48	--	--	--	--
	6/1/12	-73	19	163	0	163	-56	93	2.6	16.9	79.0	9,999	29	--	--	--	--
	6/4/12	-73	17	161	0	161	-52	92	4.2	14.2	77.9	5,995	73	--	--	--	--
	6/6/12	-73	5	162	0	162	-56	91	4.3	14.5	78.9	3,547	46	--	--	--	--
	6/8/12	-73	19	161	0	161	-53	95	4.1	14.7	80.1	3,126	28	--	--	--	--
	6/11/12	-69	15	162	0	162	-56	98	4.5	13.1	79.1	1,884	54	--	--	--	--
	6/13/12	-73	11	162	0	162	-6	97	5.0	12.6	78.6	3,012	76	--	--	--	--
	6/15/12	-75	10	162	0	162	-53	98	4.8	13.2	79.5	1,976	53	--	--	--	--
	6/18/12	-72	19	161	0	161	-53	98	5.2	13.2	79.3	3,556	48	--	--	--	--
	6/20/12	-70	4	157	0	157	-53	98	6.2	11.8	79.5	2,975	61	--	--	--	--
	6/22/12	-71	32	162	0	162	-53	99	5.6	12.2	78.0	2,359	66	--	--	--	--
	6/25/12	-70	26	160	0	160	-51	100	5.1	13.9	78.2	2,464	56	--	--	--	--
	6/27/12	-71	23	161	0	161	-52	102	5.1	13.9	79.3	2,727	42	--	--	--	--
	6/29/12	-71	25	164	0	164	-52	102	5.1	14.1	78.1	2,668	54	--	--	--	--
	7/2/12	-168	21	163	0	163	-48	102	4.8	13.5	78.1	3,116	74	--	--	--	--
	7/5/12	-71	25	163	0	163	-48	106	4.5	13.9	79.6	2,261	47	--	--	--	--
	7/9/12	-75	25	161	0	161	-53	104	5.0	14.0	77.9	1,968	63	--	--	--	--
	7/11/12	-70	25	166	0	166	-52	107	5.0	13.6	77.7	2,072	63	--	--	--	--
	7/13/12	-67	26	166	0	166	-49	106	5.1	13.9	76.1	4,927	67	--	--	--	--

Table 1
Field Measurements
Zone A Heating Evaluation
Pasco Landfill, Pasco, WA

PERIOD: 5/14 - 7/16//2012

Well	Date	Skid Vacuum (in. H_2O)	Skid LEL (%)	Well Head Airflow (cfm)	Dilution Airflow (cfm)	Total Airflow (scfm)	Well Head Vacuum (in. H_2O)	Well Head Temp (F)	Well Head CO2 (%)	Well Head O2 (%)	Well Bal Gas (%)	Well Head PID	Well Head LEL (%)	Field CH4 (%)	Field CO (ppmV)	Field NO	Field NO2
VEW-07I	5/14/12	-47	26	43	45	88	-30.3	90	6.4	7.4	86.2	3,087	100+	0	788	0	0
	5/15/12	-46	29	44	42	86	-30.2	90	6.4	8.0	85.7	4,269	100+	0	633	0	1.1
	5/16/12	-46	17	44	42	86	-30.5	88	8.0	8.0	83.9	8,211	100+	0	568	0	0
	5/17/12	-78	13	~5	0	~5	-4.2	85	8.1	6.5	85.4	4,668	100+	0	730	0	5.2
	5/21/12	-73	23	~5	0	~5	-4.1	82	8.9	6.1	84.7	6,962	100+	0	817	0	1.8
	5/23/12	-74	21	~5	0	~5	-4.7	88	9.4	6.9	74.5	4,824	100+	0	595	0	0
	5/24/12	-74	21	~5	0	~5	-4.4	85	6.7	10.1	71.8	6,944	100+	0	704	0	0
	5/25/12	-73	21	~5	0	~5	-4.5	86	8.9	6.0	70.0	3,156	100+	0	934	--	--
	5/29/12	-72	21	~5	0	~5	-4.5	87	9.3	5.7	66.6	3,038	100+	--	--	--	--
	5/31/12	-73	17	~5	0	~5	-4.6	86	9.4	5.8	73.2	4,175	100+	--	--	--	--
	6/1/12	-73	19	~5	0	~5	-4.7	83	9.9	5.3	69.3	9,999	100+	--	--	--	--
	6/4/12	-73	17	~5	0	~5	-3.3	77	10.4	5.0	69.1	4,182	100+	--	--	--	--
	6/6/12	-73	15	~5	0	~5	-5.5	78	10.3	6.3	76.6	1,361	100+	--	--	--	--
	6/8/12	-73	19	~5	0	~5	-6.0	80	9.0	6.8	75.9	3,054	100+	--	--	--	--
	6/11/12	-69	15	~5	0	~5	-7.0	94	7.8	7.1	63.1	793	100+	--	--	--	--
	6/13/12	-73	11	~5	0	~5	-7.6	85	7.4	8.3	67.6	965	100+	--	--	--	--
	6/15/12	-75	10	~5	0	~5	-8.1	88	8.6	6.8	68.1	903	100+	--	--	--	--
	6/18/12	-72	19	~5	0	~5	-8.6	83	6.0	10.4	65.8	941	100+	--	--	--	--
	6/20/12	-70	4	~5	0	~5	-8.6	94	6.4	10.4	68.7	869	100+	--	--	--	--
	6/22/12	-71	32	~5	0	~5	-8.5	94	4.6	11.7	56.1	900	100+	--	--	--	--
	6/25/12	-70	26	~5	0	~5	-9.2	93	6.8	10.1	66.6	910	100+	--	--	--	--
	6/27/12	-71	23	~5	0	~5	-9.2	92	6.5	10.5	64.5	937	100+	--	--	--	--
	6/29/12	-71	25	~5	0	~5	-9.0	92	6.1	10.9	62.5	841	100+	--	--	--	--
	7/2/12	-168	21	~5	0	~5	-9.0	94	4.8	11.9	54.0	1,002	100+	--	--	--	--
	7/5/12	-71	25	~5	0	~5	-8.5	95	6.3	10.3	71.2	1,033	100+	--	--	--	--
	7/9/12	-75	25	~5	0	~5	-7.6	93	3.9	13.9	65.3	937	100+	--	--	--	--
	7/11/12	-70	25	~5	0	~5	-8.8	97	6.2	10.2	57.6	935	100+	--	--	--	--
	7/13/12	-67	26	~5	0	~5	-8.9	95	8.6	8.2	68.1	4,950	100+	--	--	--	--
VEW-07D	5/14/12	-4	17	56	0	56	-2.8	90	3.1	17.6	79.3	1,159	24	0	8	0	0
	5/15/12	-5	21	51	0	51	-3.4	90	2.4	18.2	79.3	1,540	18	0	5	0	0
	5/16/12	-4	17	46	0	46	-3.3	88	1.1	18.5	80.2	1,881	20	0	3	0	2.2
	5/17/12	-10	19	104	0	104	-6.8	88	0.8	18.8	80.4	1,787	19	0	6	0	10.5
	5/21/12	-10	12	109	0	109	-6.9	87	0.6	19.2	80.1	1,960	14	0	8	0	6.6
	5/23/12	-10	11	107	0	107	-7.2	84	2.0	18.9	78.8	3,358	15	0	7	0	0
	5/24/12	-10	9	109	0	109	-6.4	87	1.5	19.0	78.3	9,999	23	0	10	0	0
	5/25/12	-10	10	109	0	109	-6.8	88	1.7	18.4	78.4	1,831	29	0	14	--	--
	5/29/12	-10	8	108	0	108	-7.0	88	1.8	18.4	78.8	1,576	20	--	--	--	--
	5/31/12	-10	6	104	0	104	-6.0	86	1.7	18.6	78.6	1,860	19	--	--	--	--
	6/1/12	-9	7	104	0	104	-6.4	87	1.8	18.6	78.4	9,999	21	--	--	--	--
	6/4/12	-9	5	104	0	104	-6.0	84	1.8	18.6	77.1	1,797	46	--	--	--	--
	6/6/12	-10	3	105	0	105	-7.5	86	1.9	18.6	78.1	1,642	23	--	--	--	--
	6/8/12	-10	5	114	0	114	-7.5	84	1.7	18.9	78.4	1,669	18	--	--	--	--
	6/11/12	-11	4	112	0	112	-6.6	90	1.6	18.4	78.9	989	14	--	--	--	--
	6/13/12	-9	0	102	0	102	-6.8	88	1.7	18.4	78.7	1,391	21	--	--	--	--
	6/15/12	-11	17	109	0	109	-7.8	88	1.7	18.3	78.4	1,078	29	--	--	--	--
	6/18/12	-11	7	116	0	116	-7.7	87	1.8	18.8	77.8	1,683	30	--	--	--	--
	6/20/12	-11	5	115	0	115	-7.5	89	2.0	19.4	76.8	1,563	36	--	--	--	--
	6/22/12	-11	25	111	0	111	-7.2	90	1.7	19.1	76.5	1,355	40	--	--	--	--
	6/25/12	-11	21	113	0	113	-7.1	88	1.7	19.3	77.8	1,434	22	--	--	--	--
	6/27/12	-10	19	104	0	104	-7.0	88	1.7	19.2	78.0	1,337	21	--	--	--	--
	6/29/12	-9	19	101	0	101	-7.1	88	1.7	19.5	77.0	1,444	30	--	--	--	--
	7/2/12	-8	21	88	0	88	-5.0	90	1.5	19.0	78.1	1,466	27	--	--	--	--
	7/5/12	-9	21	82	0	82	-6.5	90	1.5	18.9	78.2	1,176	27	--	--	--	--
	7/9/12	-9	19	108	0	108	-7.2	90	1.7	19.3	77.1	1,115	32	--	--	--	--
	7/11/12	--	19	0	0	0	-0.4	--	--	--	--	--	32	--	--	--	--
	7/13/12	-10	17	106	0	106	-7.1	92	1.9	18.9	77.8	1,758	26	--	--	--	--

epi ENVIRONMENTAL PARTNERS INC

PERIOD: 5/14 - 7/16//2012

TABLE 2
VOC Concentrations
Detected Compounds Only (in µg/L)
Pasco Landfill, Pasco, WA

Location	Sample Date	Chloroethenes						Chloroethanes					Chloromethanes			Chlorobenzenes						Aromatic Compounds				
		Tetra chloro ethene	Trichloro ethene	1,1-Dichloro ethene	Cis-1,2-Dichloro ethene	Trans-1,2-Dichloro ethene	Vinyl Chloride	1,1,1-Trichloro ethane	1,1,2-Trichloro ethane	1,1-Dichloro ethane	1,2-Dichloro ethane	Chloro ethane	Chloro form	Methylene Chloride	Chloro methane	1,2,3-Trichloro benzene	1,2,4-Trichloro benzene	1,2-Dichloro benzene	1,3-Dichloro benzene	1,4-Dichloro benzene	Chloro benzene	Benzene	Ethyl benzene	1,2,4-Trimethyl benzene	1,3,5-Trimethyl benzene	n-Propyl benzene
Flare Inlet	6/18/12	27	340	0.56	6.2	< 0.20 U	0.34	42	< 0.20 U	25	21	1	2.7	390	0.92	< 0.20 U	< 0.20 U	1.2	< 0.20 U	< 0.20 U	0.39	3.4	310	42	28	13
	7/16/12	33	220	0.42	5.6	< 0.20 U	0.11	28	< 0.20 U	22	18	0.78	2.2	450	0.8	< 0.20 U	< 0.20 U	1.6	< 0.20 U	< 0.20 U	0.55	2.8	230	63	44	27
SVE Skid	6/18/12	36	500	0.57	7	< 0.20 U	0.37	44	< 0.20 U	27	24	0.96	2.9	530	1	< 0.20 U	< 0.20 U	3.2	< 0.20 U	0.33	0.62	3.9	550	79	47	29
VEW-6S	5/16/12	40	300	0.45	12	0.24	0.48	5.1	< 0.20 U	22	32	1.9	4.8	340	1.5	< 0.20 U	< 0.20 U	0.71	< 0.20 U	< 0.20 U	0.28	2.6	110	29	15	6
	5/17/12	54	420	0.69	15	0.36	0.81	10	< 0.20 U	28	35	2.3	4.8	380	2.4	< 0.20 U	< 0.20 U	1.1	< 0.20 U	< 0.20 U	0.43	4	330	40	32	11
	5/21/12	39	220	0.41	8.3	0.22	0.4	7.9	< 0.20 U	22	36	1.1	3.4	240	1	< 0.20 U	0.22	0.92	< 0.20 U	< 0.20 U	0.33	3.1	160	32	26	7.9
	5/23/12	42	240	0.43	8.7	< 0.20 U	0.45	9.3	< 0.20 U	20	32	1.2	3.7	260	1.1	< 0.20 U	0.7	1.2	< 0.20 U	0.27	0.47	3.4	210	39	31	11
	5/29/12	38	270	0.4	7.1	< 0.20 U	0.37	8.5	< 0.20 U	16	28	1	3.5	210	0.89	< 0.20 U	0.28	1.2	< 0.20 U	0.24	0.35	2.8	150	35	27	11
	6/4/12	42	390	0.55	8.7	< 0.20 U	0.51	11	< 0.20 U	23	35	1.2	5	420	1.2	< 0.20 U	< 0.20 U	1.1	< 0.20 U	0.22	0.43	3.7	160	39	30	13
	6/11/12	36	270	0.3	7.5	< 0.20 U	0.27	6.7	< 0.20 U	21	31	0.64	3.9	390	0.72	< 0.20 U	< 0.20 U	1.4	< 0.20 U	0.21	0.33	3	140	34	30	11
	6/18/12	49	330	0.51	8.2	0.21	0.51	< 0.20 U	< 0.20 U	23	35	1.3	4.8	420	1.3	< 0.20 U	< 0.20 U	1.2	< 0.20 U	0.25	0.41	4	260	49	36	14
	6/25/12	40	210	0.56	8.5	0.23	0.48	8.3	< 0.20 U	21	31	1.3	4.7	380	1.1	< 0.20 U	0.94	1.3	< 0.20 U	0.29	0.65	3.4	140	39	30	14
	7/2/12	19	130	0.35	3.9	< 0.20 U	0.27	3.5	< 0.20 U	9	14	0.8	2.1	730	0.59	< 0.20 U	0.6	0.37	< 0.20 U	< 0.20 U	0.25	1.7	93	15	13	7.2
	7/9/12	56	310	0.71	9.6	0.24	0.68	9.5	< 0.20 U	30	37	1.7	5.1	620	1.4	< 0.20 U	0.89	0.94	< 0.20 U	0.22	0.52	3.8	250	67	50	< 0.20 U
	7/16/12	23	160	0.31	5.7	< 0.20 U	0.22	4.6	< 0.20 U	14	24	1.1	2.8	530	0.86	< 0.20 U	0.21	1.3	< 0.20 U	< 0.20 U	0.43	2.5	140	31	22	11
VEW-6I	5/16/12	140	1100	2.4	49	0.92	2.6	58	< 0.20 U	100	150	3.4	16	1,500	9.4	< 0.20 U	< 0.20 U	5	< 0.20 U	1.1	2	27	820	130	77	54
	5/17/12	220	3000	3.8	49	1.1	4.3	85	< 0.20 U	130	210	5.6	26	3,000	11	< 0.20 U	< 0.20 U	5.7	< 0.20 U	1.3	2.8	33	1,300	130	74	58
	5/21/12	110	1300	2.5	36	0.8	2.7	70	< 0.20 U	110	170	3.3	17	1,400	5.4	< 0.20 U	< 0.20 U	3.4	< 0.20 U	0.72	2.2	25	1,100	72	47	35
	5/23/12	140	1100	2.6	36	0.87	2.7	74	< 0.20 U	110	140	3.6	19	1,200	5.9	< 0.20 U	< 0.20 U	2.4	< 0.20 U	0.61	2.4	27	940	89	60	50
	5/29/12	150	3100	2.5	36	0.78	2.3	83	< 0.20 U	100	170	3.2	19	1,200	5.2	< 0.20 U	< 0.20 U	4.5	< 0.20 U	0.97	2.3	25	1,400	130	76	56
	6/4/12	160	3600	3.1	37	0.82	3.4	84	< 0.20 U	120	160	3.9	23	1,300	7.2	< 0.20 U	< 0.20 U	2.2	< 0.20 U	0.57	2.4	28	1,400	82	57	46
	6/11/12	260	2400	3.1	33	0.75	2.2	57	< 0.20 U	98	160	2.6	16	1,300	5.3	< 0.20 U	< 0.20 U	4.3	< 0.20 U	0.88	2.8	24	2,500	150	100	89
	6/18/12	150	2400	3.1	39	0.86	3.2	55	< 0.20 U	120	190	4	21	1,400	8.3	< 0.20 U	< 0.20 U	2.2	< 0.20 U	0.53	2	33	1,200	84	55	51
	6/25/12	160	1300	2.1	36	0.66	1.5	54	< 0.20 U	100	140	2.1	13	1,100	4	< 0.20 U	< 0.20 U	2.9	< 0.20 U	0.68	1.8	24	1,400	130	84	64
	7/2/12	140	1400	2.9	39	0.68	2.7	50	< 0.20 U	110	140	3.4	14	3,200	5.4	< 0.20 U	0.4	0.41	< 0.20 U	< 0.20 U	1.7	27	910	26	26	29
	7/9/12	140	1400	3.3	44	0.88	2.7	62	< 0.20 U	120	170	3.2	18	1,500	5.7	< 0.20 U	0.24	0.9	< 0.20 U	0.22	2	27	1,200	48	38	33
	7/16/12	160	1500	2.6	37	0.74	2.1	42	< 0.20 U	98	140	2.5	11	1,500	4.6	< 0.20 U	< 0.20 U	2	< 0.20 U	0.49	2	23	1,600	120	88	75
VEW-6D	5/16/12	9.7	84	< 0.20 U	1.2	< 0.20 U	< 0.020 U	4.4	< 0.20 U	2.2	6	< 0.20 U	6.2	14	< 0.20 U	< 0.20 U	< 0.20 U	0.55	< 0.20 U	< 0.20 U	< 0.20 U	0.45	60	8.2	5.3	2.9
	5/17/12	13	110	< 0.20 U	1.5	< 0.20 U	< 0.020 U	5.4	< 0.20 U	2.6	6.7	< 0.20 U	6	16	< 0.20 U	< 0.20 U	< 0.20 U	0.78	< 0.20 U	< 0.20 U	< 0.20 U	0.55	90	12	7.3	4.4
	5/21/12	7.8	84	< 0.20 U	0.77	< 0.20 U	< 0.020 U	3.4	< 0.20 U	1.4	4.9	< 0.20 U	2.2	8	< 0.20 U	< 0.20 U	< 0.20 U	0.56	< 0.20 U	< 0.20 U	< 0.20 U	0.27	76	8.7	5.7	3
	5/23/12	12	75	< 0.20 U	0.95	< 0.20 U	< 0.020 U	4.3	< 0.20 U	1.8	5.9	< 0.20 U	2.4	10	< 0.20 U	0.24	0.83	0.85	< 0.20 U	< 0.20 U	< 0.20 U	0.39	79	14	9.5	5.5
	5/29/12	12	73	< 0.20 U	0.93	< 0.20 U	< 0.020 U	4.2	< 0.20 U	1.6	5.4	< 0.20 U	2.3	9	< 0.20 U	< 0.20 U	< 0.20 U	0.72	< 0.20 U	< 0.20 U	< 0.20 U	0.35	75	14	8.9	5.2
	6/4/12	12	66	< 0.20 U	0.87	< 0.20 U	< 0.020 U	4.5	< 0.20 U	1.6	5.6	< 0.20 U	2.8	9	< 0.20 U	< 0.20 U	< 0.20 U	0.71	< 0.20 U	< 0.20 U	< 0.20 U	0.33	70	15	9.8	5.2
	6/11/12	13	55	< 0.20 U	0.83	< 0.20 U	< 0.020 U	4.2	< 0.20 U	1.3	4.4	< 0.20 U	2	7	< 0.20 U	< 0.20 U	< 0.20 U	1.2	< 0.20 U	< 0.20 U	< 0.20 U	0.34	69	13	16	11
	6/18/12	11	66	< 0.20 U	0.67	< 0.20 U	< 0.020 U	3.1	< 0.20 U	1.3	4.6	< 0.20 U	1.9	7	< 0.20 U	< 0.20 U	< 0.20 U	0.75	< 0.20 U	< 0.20 U	< 0.20 U	0.34	75	14	8.8	5.8
	6/25/12	13	45	< 0.20 U	0.67	< 0.20 U	< 0.020 U	3.3	< 0.20 U	1.2	3.7	< 0.20 U	1.8	6	< 0.20 U	< 0.20 U	0.95	0.56	< 0.20 U	< 0.20 U	< 0.20 U	0.41	58	12	12	7.3
	7/2/12	12	79	< 0.20 U	0.57	< 0.20 U	< 0.020 U	3	< 0.20 U	1	3.5	< 0.20 U	2.1	5	< 0.20 U	< 0.20 U	0.6	0.47	< 0.20 U	< 0.20 U	< 0.20 U	0.38	120	21	12	6.5
	7/9/12	11	53	< 0.20 U	0.69	< 0.20 U	< 0.020 U	2.9	< 0.20 U	1.2	3.6	< 0.20 U	2.1	6	< 0.20 U	< 0.20 U	0.65	0.54	< 0.20 U	< 0.20 U	< 0.20 U	0.38	89	26	11	5.8
	7/16/12	13	39	< 0.20 U	0.53	< 0.20 U	< 0.020 U	2.5	< 0.20 U	0.73	3.2	< 0.20 U	2.4	4	< 0.20 U	< 0.20 U	< 0.20 U	0.83	< 0.20 U	< 0.20 U	< 0.20 U	0.23	53	9.4	15	8.3
VEW-7S	5/16/12	42	420	0.67	13	0.23	0.49	27	< 0.20 U	34	14	1.9	2.5	990	1.5	< 0.20 U	< 0.20 U	2	< 0.20 U	< 0.20 U	0.88	3.3	780	130	85	45
	5/17/12	48	490	0.61	12	0.21	0.44	31	< 0.20 U	35	14	1.7	1.6	1,300	1.2	< 0.20 U	< 0.20 U	2.2	< 0.20 U	< 0.20 U	0.87	3.3	910	140	96	54
	5/21/12	31	250	0.69	11	< 0.20 U	0.39	93	< 0.20 U	26	14	1.3	1.4	810	0.75	< 0.20 U	< 0.20 U	2.4	< 0.20 U	0.24	0.92	3.4	450	110	72	37
	5/23/12	37	280	1.1	8.2	< 0.20 U	0.41	350	< 0.20 U	30	13	1.1	1.1	770	0.54	< 0.20 U	0.27	2.5	< 0.20 U	0.29	0.88	3	580	130	89	50
	5/29/12	38	300	1.3	10	0.2	0.44	230	< 0.20 U	33	28	1.3	1.7	610	0.79	< 0.20 U	< 0.20 U	2.8	< 0.20 U	0.27	1.1	3.7	560	150	99	55
	6/4/12	42	500	1.2	12	0.26	0.71	250	< 0.20 U	42	24	1.9	2.5	700	1.4	< 0.20 U	< 0.20 U	3.3	< 0.20 U	0.35	1.5	5.7	760	200	110	66
	6/11/12	46	320	0.89	11	0.25	0.32	140	< 0.20 U	40	20	0.76	2.1	670	0.98	< 0.20 U	< 0.20 U	3.4	< 0.20 U	0.32	1.3	4.3	530	170	120	87
	6/18/12	46	510	1.1	13	0.26	0.79	120	< 0.20 U	51	30	2.1	2.7	650	2	< 0.20 U	< 0.20 U	4	< 0.20 U	0.39	1.1	7.1	720	110	74	52
	6/25/12	55	350	1.1	13	< 0.20 U	0.61	110	< 0.20 U	43	28	1.9	2.7	490	1.5	< 0.20 U	0.28	4.1	< 0.20 U	0.45	1.5	6	550	150	100	68
	7/2/12	41	370	0.71	7.4	< 0.20 U	0.41	76	< 0.20 U	36	22	1.1	1.6	670	1.1	< 0.20 U	0.38	0.73	< 0.20 U	< 0.20 U	0.76	3.8	480	50	44	35
	7/9/12	49	490	1.3	13	< 0.20 U	0.8	95	< 0.20 U	55	30	2.4	2.8	640	2	< 0.20 U	0.24	4.5	0.21	0.49	1.5	6	1,000	130	86	52
	7/16/12	53	290	0.69	8.8	< 0.20 U	0.37	64	< 0.20 U	41	24	1.5	1.8	480	1.6	< 0.20 U	< 0.20 U	3.9	< 0.20 U	0.44	1.2	4.3	530	180	110	74
VEW-7I	5/16/12	130	1400	4.2	37	1.2	2.7	140	< 0.20 U	150	100	6.3	5.7	6,200	4.9	< 0.20 U	< 0.20 U	7.6	< 0.20 U	0.81	2.4	24	1,100	100	67	53
	5/17/12	150	11000	4.8	47	1.2	3.5	220	< 0.20 U	210	88	6.7	5.4	8,700	5.1	< 0.20 U	< 0.20 U	13	< 0.20 U	1.3	2.3	31	16,000	120	74	59
	5/21/12	97	1500	3.5	30	0.5	1.7	790	< 0.20 U	160	70	2.8	2.7	3,900	2.1	< 0.20 U	< 0.20 U	4.9	< 0.20 U	0.5	1.2	25	1,000	61	40	31
	5/23/12	120	1300	8.9	33	0.79	3.2	4900	< 0.20 U	150	77	4.4	3.8	3,800	2.8	< 0.20 U	< 0.20 U	4.5	< 0.20 U	0.59	1.9	26	790	71	48	40
	5/29/12	140	1300	9.6	35	1	3.4	3400	< 0.20 U	170	80	5.3	4.4	4,200	3.4	< 0.20 U	< 0.20 U	7.6	< 0.20 U	0.85	2.1	27	860	80	54	47
	6/4/12	180	2300	6.4	40	1	4.9	1400	< 0.20 U	260	100	7.9	5.2	5,900	5.8	< 0.20 U	< 0.20 U	4	< 0.20 U	0.52	2.2	34	1,400	77	57	61
	6/11/12	270	3100	4.5	35	0.92	1.5	410	< 0.20 U	180	110	5	4.2	8,100	3	< 0.20 U	< 0.20 U	4	< 0.20 U	0.44	2.4	24	3,100	140	100	99
	6/18/12	270	3500	5.9	39	1.3	3.7	270	< 0.20 U	230	140	8.7	5.4	7,600	6.5	< 0.20 U	< 0.20 U	1.2	< 0.20 U	< 0.20 U	2.2	35	1,400	51	37	40
	6/25/12	310	3500	4.1	36	0.79	1.9	270	< 0.20 U	210	110	4.5	4.5	6,200	3.4	< 0.20 U	< 0.20 U	1.7	< 0.20 U	0.23	2.2	27	3,500	85	64	58
	7/2/12	540	3300	5.3	43	0.99	2.4	730	< 0.20 U	740	150	6.4	5.1	5,200	4.1	< 0.20 U	< 0.20 U	0.35	< 0.20 U	< 0.20 U	2.6	33	2,200	38	39	47
	7/9/12	150	2900	4.4	33	0.7	2.1	300	< 0.20 U	210	110	4.7	5.6	3,000	3.5	< 0.20 U	< 0.20 U	3.3	< 0.20 U	0.41	2.2	24	1,500	94	66	50
	7/16/12	160	2200	3.1	28	0.5	1.4	220	< 0.20 U	160	100	3	4	3,500	2.4	< 0.20 U	< 0.20 U	3.2	< 0.20 U	0.4	2	21	1,600	130	88	72
VEW-7D	5/16/12	7.1	180	0.28	1.3	< 0.20 U	< 0.020 U	9.9	< 0.20 U	7.3	5.2	< 0.20 U	3.2	47	< 0.20 U	< 0.20 U	< 0.20 U	1.5	< 0.20 U	< 0.20 U	< 0.20 U	0.95	200	44	13	6.9
	5/17/12	13	230	0.47	1.7	< 0.20 U	0.047	15	< 0.20 U	10	6.4	< 0.20 U	4.1	49	< 0.20 U	< 0.20 U	< 0.20 U	2.5	0.25	< 0.20 U	0.31	1.5	310	62	38	15
	5/21/12	7.4	150	< 0.20 U	1	< 0.20 U	< 0.020 U	9.3	< 0.20 U	6.3	5.2	< 0.20 U	1.7	31	< 0.20 U	< 0.20 U	< 0.20 U	2.5	0.23	0.23	0.24	0.93	160	43	26	9.7
	5/23/12	7.5	160	< 0.20 U	0.9	< 0.20 U	< 0.020 U	7.9	< 0.20 U	5	3.9	< 0.20 U	1.2	32	< 0.20 U	< 0.20 U	0.4	3.3	< 0.20 U	0.45	0.22	0.7	210	76	41	12
	5/29/12	9.7	150	0.31	1.1	< 0.20 U	0.031	11	< 0.20 U	6.9	4.7	< 0.20 U	1.6	31	< 0.20 U	< 0.20 U	< 0.20 U	2.3	0.23	< 0.20 U	0.27	0.97	160	41	27	13
	6/4/12	11	150	0.38	1.2	< 0.20 U	0.035	13	< 0.20 U	8.4	5.4	< 0.20 U	2.1	35	< 0.20 U	< 0.20 U	< 0.20 U	2.2	0.22	< 0.20 U	0.29	1.1	140	36	25	13
	6/11/12	11	130	0.22	1	< 0.20 U	< 0.020 U	9.4	< 0.20 U	6	4.3	< 0.20 U	1.2	33	< 0.20 U	< 0.20 U	< 0.20 U	2.1	0.22	< 0.20 U	0.3	0.95	140	30	23	11
	6/18/12	9.7	140	0.29	1	< 0.20 U	< 0.020 U	9.8	< 0.20 U	7.7	4.6	< 0.20 U	1.5	30	< 0.20 U	< 0.20 U	< 0.20 U	2	< 0.20 U	< 0.20 U	0.24	1.2	140	43	25	13
	6/25/12	8.5	94	0.26	0.73	< 0.20 U	< 0.020 U	7	< 0.20 U	4.5	2.9	< 0.20 U	0.96	16	< 0.20 U	< 0.20 U	0.33	1.7	< 0.20 U	< 0.20 U	0.21	0.77	110	31	19	12
	7/2/12	9.5	150	0.35	0.86	< 0.20 U	0.022	9.2	< 0.20 U	6.1	3.4	< 0.20 U	1.4	41	< 0.20 U	< 0.20 U	0.33	0.34	< 0.20 U	< 0.20 U	0.24	0.97	290	15	12	7.6
	7/9/12	10	150	0.36	1.1	< 0.20 U	0.027	9.4	< 0.20 U	6.9	4.1	< 0.20 U	1.6	28	< 0.20 U	< 0.20 U	0.3	2.5	0.21	0.26	0.28	1.1	180	62	38	13
	7/16/12	13	100	< 0.20 U	0.91	< 0.20 U	< 0.020 U	8.5	< 0.20 U	5.4	3.7	< 0.20 U	1.3	22	< 0.20 U	< 0.20 U	< 0.20 U	2.8	0.2	0.33	0.34	0.9	130	44	25	12

Note: Compound names in blue comprise greater than 1%, on average, of the total VOCs detected.

PERIOD: 5/14 - 7/16//2012

TABLE 2
VOC Concentrations
Detected Compounds Only (in µg/L)
Pasco Landfill, Pasco, WA

Location	Sample Date	Aromatic Compounds							Ketones				PAHs	Other VOCs									Total VOCs
		Isopropyl benzene (Cumene)	n-Butyl benzene	Sec-Butyl benzene	Toluene	p-Isopropyl toluene	m, p-Xylene	o-Xylene	Methyl isobutyl ketone	2-Butanone	Acetone	2-Hexanone	Naph thalene	CFC-11	Carbon Disulfide	1,2,3-Trichloro propane	Bromo chloro methane	Bromo methane	Cis-1,3-Dichloro propene	Tertiary butyl alcohol	CFC-12	Ethanol	
Flare Inlet	6/18/12	6.8	1.1	< 0.20 U	3,800	0.69	900	250	670	1,700	1,200	< 1.0 U	0.2	7.1	0.38	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.63	500	10,292
	7/16/12	10	1.9	< 0.20 U	3,500	1.3	790	200	540	1,200	930	< 1.0 U	< 0.20 U	6.2	0.3	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	360	8,690
SVE Skid	6/18/12	11	2.2	< 0.20 U	5,200	1.2	1,700	460	930	2,200	1,400	< 1.0 U	0.68	7.4	0.39	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.62	620	14,420
VEW-6S	5/16/12	3.7	0.78	< 0.20 U	1,300	0.62	620	120	170	220	390	< 1.0 U	0.21	2.6	0.26	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	2.5	40	3,795
	5/17/12	6.9	1.4	< 0.20 U	2,600	1.1	1,200	330	340	570	360	13	0.29	2.8	0.53	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	47	6,845
	5/21/12	5.1	0.92	< 0.20 U	1,300	0.66	530	150	180	120	120	5.6	0.25	1.2	0.24	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	40	3,264
	5/23/12	7.1	1.5	< 0.20 U	1,700	1.1	700	190	220	140	100	12	0.42	1.5	0.27	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.57	26	4,016
	5/29/12	5.9	1.4	< 0.20 U	1,400	0.98	660	150	210	150	130	10	0.31	1.3	0.24	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	44	3,576
	6/4/12	8	1.6	< 0.20 U	2,000	1.2	590	140	220	240	280	14	0.2	2	0.31	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	45	4,728
	6/11/12	5.6	1.3	< 0.20 U	1,400	1.1	570	160	220	330	140	14	0.22	1.3	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.64	50	3,882
	6/18/12	6.9	1.4	< 0.20 U	1,900	1.1	880	250	340	580	320	< 1.0 U	0.24	2	0.26	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	4	1.1	67	5,593
	6/25/12	12	2.4	< 0.20 U	1,000	2.1	470	130	230	400	270	< 1.0 U	0.27	2.3	0.29	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.91	72	3,529
	7/2/12	4.4	0.59	< 0.20 U	2,500	0.53	270	77	140	1,100	150	7.4	< 0.20 U	1.2	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.55	< 4.0 U	5,296
	7/9/12	9.6	1.3	< 0.20 U	1,900	1.3	850	200	310	580	420	< 1.0 U	0.24	2.9	0.3	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	1.3	120	5,852
	7/16/12	8.7	2.1	< 0.20 U	1,200	1.8	380	120	200	450	290	< 1.0 U	0.25	1.3	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	100	3,729
VEW-6I	5/16/12	36	3.5	< 0.20 U	63,000	2.7	2,500	720	2,700	9,200	6,800	140	0.74	6.1	3.8	< 0.20 U	< 0.20 U	0.88	< 0.20 U	< 0.80 U	5.4	2,400	91,767
	5/17/12	39	4.5	< 0.20 U	76,000	3.7	12,000	1,200	4,800	14,000	10,000	210	0.41	5.5	4.7	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	9.7	2,800	129,428
	5/21/12	23	2.2	< 0.20 U	69,000	1.7	6,600	970	3,000	6,100	2,800	110	0.26	2.6	2.3	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	49	2.6	2,900	96,077
	5/23/12	34	1.8	< 0.20 U	66,000	1.5	3,000	850	3,100	6,600	2,900	150	< 0.20 U	2.4	2.5	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	38	2.6	1,400	88,089
	5/29/12	33	3.6	< 0.20 U	64,000	2.6	10,000	1,200	3,600	7,200	3,300	150	0.56	2.1	2.3	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	48	2	2,300	98,411
	6/4/12	33	2	< 0.20 U	89,000	1.8	11,000	1,200	3,900	9,200	5,900	140	< 0.20 U	2.6	2.7	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	56	2.9	2,900	130,462
	6/11/12	44	5.7	< 0.20 U	69,000	4.8	7,700	1,400	3,500	8,500	5,600	180	0.36	2.1	2.3	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	3.9	2,100	105,252
	6/18/12	30	1.5	2.1	73,000	1.4	6,300	920	3,900	12,000	6,400	270	< 0.20 U	1.8	2.2	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	3.9	3,000	111,655
	6/25/12	40	2.4	< 0.20 U	52,000	2.4	8,900	990	4,100	9,300	4,900	130	< 0.20 U	1.3	1.4	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	34	2.3	2,000	87,025
	7/2/12	27	0.47	< 0.20 U	11,000	0.73	2,500	540	2,300	8,000	5,400	140	< 0.20 U	1.8	1.6	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	4.4	650	36,695
	7/9/12	26	0.87	< 0.20 U	65,000	1.2	8,000	750	3,200	11,000	6,300	140	< 0.20 U	2.8	1.7	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	6.3	2,000	101,248
	7/16/12	41	1.9	< 0.20 U	54,000	2.4	5,500	1,300	3,400	9,300	5,300	220	< 0.20 U	1.4	1.5	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	37	4.9	1,800	86,321
VEW-6D	5/16/12	1.8	0.25	< 0.20 U	740	< 0.20 U	180	45	250	1,400	2,100	6.4	< 0.20 U	< 0.20 U	0.48	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	1.4	< 4.0 U	4,930
	5/17/12	2.6	0.34	< 0.20 U	1,200	0.23	290	72	360	1,600	1,900	8.7	< 0.20 U	< 0.20 U	0.53	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	7	1.5	33	5,752
	5/21/12	1.7	0.23	< 0.20 U	850	< 0.20 U	220	56	260	770	690	4.4	< 0.20 U	< 0.20 U	0.32	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	4.1	0.46	19	3,083
	5/23/12	2.6	0.63	< 0.20 U	1,000	0.26	240	61	260	710	510	6.2	0.35	< 0.20 U	0.39	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	4.2	0.52	22	3,041
	5/29/12	2.8	0.44	< 0.20 U	680	0.27	220	56	240	630	500	6.1	< 0.20 U	< 0.20 U	0.35	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.55	37	2,586
	6/4/12	3	0.47	< 0.20 U	1,100	0.29	210	56	350	1,300	1,400	8.6	< 0.20 U	< 0.20 U	0.36	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	5.9	0.64	31	4,670
	6/11/12	4.3	1.2	< 0.20 U	630	0.87	190	47	230	870	1,000	8.7	< 0.20 U	< 0.20 U	0.27	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	6.5	0.53	31	3,219
	6/18/12	2.4	0.44	< 0.20 U	770	0.29	210	55	270	1,200	1,300	< 1.0 U	0.21	< 0.20 U	0.26	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	6.4	0.59	38	4,054
	6/25/12	3.3	0.62	< 0.20 U	410	0.47	170	43	170	650	590	7.7	< 0.20 U	< 0.20 U	0.28	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	5	0.54	29	2,246
	7/2/12	3.3	0.65	< 0.20 U	780	0.46	890	89	160	590	640	6.4	< 0.20 U	< 0.20 U	0.25	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	6.3	0.61	48	3,482
	7/9/12	3.3	0.59	< 0.20 U	580	0.43	270	69	160	800	900	7	< 0.20 U	< 0.20 U	0.32	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	6.3	0.56	53	3,064
	7/16/12	3.6	0.88	< 0.20 U	420	0.57	160	41	150	790	860	< 1.0 U	< 0.20 U	< 0.20 U	0.24	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	5.7	0.9	69	2,654
VEW-7S	5/16/12	26	2.9	< 0.20 U	5,900	1.7	2,500	750	800	1,500	3,300	< 1.0 U	0.31	30	0.71	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	2	520	17,927
	5/17/12	31	2.8	< 0.20 U	8,100	1.5	2,900	850	920	1,900	1,700	< 1.0 U	0.5	40	0.64	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	1.6	500	20,090
	5/21/12	21	3.3	< 0.20 U	5,500	1.6	1,400	450	650	720	590	< 1.0 U	0.76	28	0.46	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.7	410	11,691
	5/23/12	26	3.5	< 0.20 U	5,400	1.9	1,900	570	660	750	580	< 1.0 U	0.86	14	0.37	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.44	700	12,955
	5/29/12	28	4.5	< 0.20 U	5,900	2.3	1,700	510	750	840	620	< 1.0 U	0.61	24	0.5	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	2.1	510	13,019
	6/4/12	32	6.6	< 0.20 U	14,000	3.4	2,400	610	760	990	1,000	< 1.0 U	0.45	34	0.74	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	1.5	570	23,134
	6/11/12	35	5.5	< 0.20 U	8,900	3.1	1,500	410	1,100	2,200	1,300	< 1.0 U	0.3	14	0.49	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	12	0.58	620	18,270
	6/18/12	24	3.6	2.9	9,500	2.1	2,000	580	1,300	3,000	1,600	< 1.0 U	0.23	29	0.81	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.81	1,100	21,541
	6/25/12	34	4.9	4.1	7,300	3.2	1,600	470	1,200	2,500	1,100	< 1.0 U	0.34	22	0.75	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	14	0.72	760	16,991
	7/2/12	21	0.85	< 0.20 U	3,900	0.92	1,300	330	960	1,700	1,100	28	< 0.20 U	14	0.4	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	690	11,887
	7/9/12	29	6.7	< 0.20 U	8,900	2.8	3,100	820	1,200	2,700	1,400	< 1.0 U	0.57	31	0.69	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	0.94	1,200	22,054
	7/16/12	35	5.2	< 0.20 U	6,500	3.6	1,600	430	1,200	2,400	1,300	< 1.0 U	0.4	22	0.47	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	720	16,087
VEW-7I	5/16/12	37	2.4	< 0.20 U	97,000	1.6	3,200	870	4,400	11,000	8,800	< 1.0 U	0.48	55	4.5	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	5.7	4,500	139,413
	5/17/12	38	2.7	< 0.20 U	120,000	1.9	53,000	1,100	14,000	26,000	21,000	70	0.48	66	6.3	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	8.4	3,700	275,736
	5/21/12	22	0.82	< 0.20 U	110,000	0.5	3,000	830	4,000	7,200	3,600	39	0.31	38	2.4	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	39	2.2	2,100	138,598
	5/23/12	27	1.3	< 0.20 U	91,000	0.92	2,100	560	3,800	7,600	3,000	39	0.34	39	3.2	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	35	2.2	1,800	121,394
	5/29/12	31	2	< 0.20 U	110,000	1.3	2,300	600	5,000	8,200	3,800	< 1.0 U	0.42	35	3.9	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	47	24	2,200	142,675
	6/4/12	38	2.1	< 0.20 U	31,000	1.5	3,400	760	4,300	6,300	1,700	< 1.0 U	0.24	37	3.4	< 0.20 U	4.6	< 0.20 U	< 0.20 U	47	7.7	3,400	62,848
	6/11/12	49	2.6	< 0.20 U	130,000	2.1	8,900	1,300	6,000	12,000	6,900	< 1.0 U	0.24	24	1.4	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	43	1.5	3,200	184,118
	6/18/12	24	0.76	< 0.20 U	81,000	0.59	6,900	870	5,800	14,000	8,200	< 1.0 U	< 0.20 U	59	1.5	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	4,900	135,403
	6/25/12	36	1.3	< 0.20 U	81,000	1.1	11,000	1,300	7,200	13,000	6,600	71	< 0.20 U	49	1.1	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	20	0.65	2,800	137,473
	7/2/12	39	0.43	< 0.20 U	18,000	0.55	6,200	1,200	5,500	14,000	7,900	< 1.0 U	< 0.20 U	91	0.93	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	4,100	70,119
	7/9/12	32	2	< 0.20 U	90,000	1.7	9,000	1,000	4,200	9,000	6,200	< 1.0 U	< 0.20 U	46	1.7	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	1.5	3,300	131,249
	7/16/12	38	2.4	< 0.20 U	63,000	2	6,500	1,100	4,000	8,400	4,900	< 1.0 U	< 0.20 U	39	1.2	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	2,000	98,282
VEW-7D	5/16/12	3.8	0.51	< 0.20 U	1,100	0.28	750	170	290	1,300	1,500	< 1.0 U	0.25	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	240	5,882
	5/17/12	8.1	1.1	< 0.20 U	1,600	0.68	1,200	290	380	1,500	1,500	< 1.0 U	0.4	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	290	7,530
	5/21/12	4.8	0.96	< 0.20 U	1,100	0.45	470	150	340	1,000	650	< 1.0 U	0.85	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	210	4,382
	5/23/12	5.6	2.4	< 0.20 U	1,000	1.1	710	180	270	660	410	5.9	1.1	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	4.6	< 0.20 U	690	4,503
	5/29/12	6.3	1.1	< 0.20 U	840	0.59	520	150	260	620	350	< 1.0 U	0.32	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	210	3,419
	6/4/12	6.9	1.2	< 0.20 U	10,000	0.63	1,000	130	380	940	640	< 1.0 U	0.33	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	210	13,753
	6/11/12	8.1	1.9	< 0.20 U	640	1.2	350	110	240	720	610	< 1.0 U	0.27	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	150	3,235
	6/18/12	5.3	0.99	< 0.20 U	860	0.59	570	120	270	1,000	760	< 1.0 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	250	4,266
	6/25/12	5.4	1.2	< 0.20 U	350	0.69	230	100	160	540	500	< 1.0 U	0.33	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	140	2,337
	7/2/12	4.6	0.49	< 0.20 U	2,500	0.42	850	140	640	1,800	1,200	< 1.0 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	160	7,844
	7/9/12	6.2	2.1	< 0.20 U	930	0.86	630	140	200	910	1,100	< 1.0 U	0.5	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	250	4,679
	7/16/12	8	2.6	< 0.20 U	590	1.7	240	120	190	700	380	< 1.0 U	0.51	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.20 U	< 0.80 U	< 0.20 U	160	2,763

Note: Compound names in blue comprise greater than 1%, on average, of the total VOCs detected.

ATTACHMENT E
PHOTOS OF PROPOSED SETTLEMENT PLATE LOCATIONS
(NOT INCLUDED)

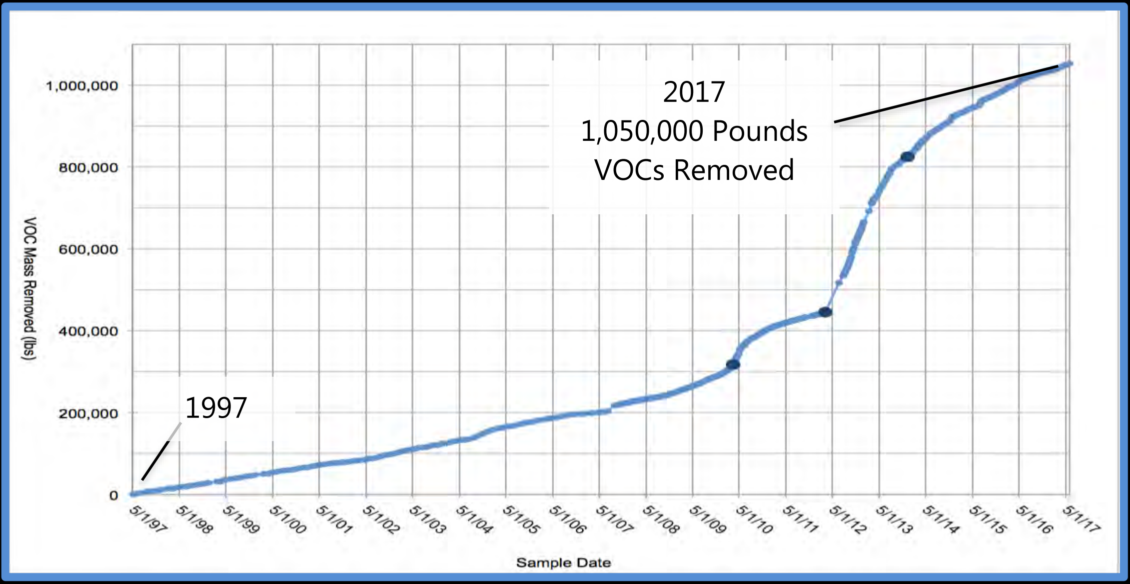
APPENDIX L
TECHNICAL REVIEW OF THE PASCO LANDFILL ZONE A SOIL VAPOR EXTRACTION SYSTEM: PAST PERFORMANCE AND FUTURE PROJECTIONS
PASCO LANDFILL NPL SITE

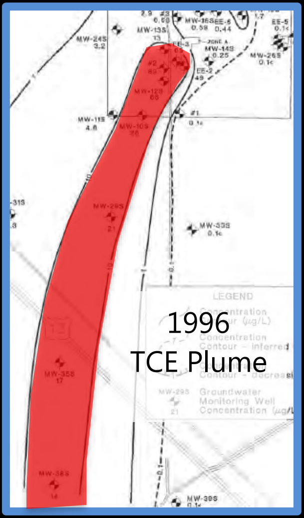
Prepared by

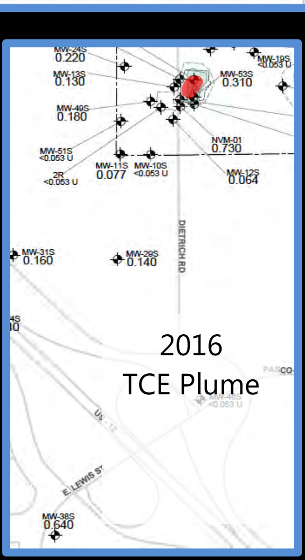
GSI Environmental

SCS Engineers

August 2017







Technical Review of the Pasco Landfill Zone A Soil Vapor Extraction System: Past Performance and Future Projections

June 2017 DRAFT

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GSI ENVIRONMENTAL
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TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report reviews the past performance and provides an analysis and projections regarding the safety and effectiveness of more intensive Soil Vapor Extraction (SVE) operations in the future.

Site History

Approximately 35,000 drums of industrial waste were disposed in Zone A between April 1972 and mid-1975. The drums contained a variety of chemicals including paint waste, metal cleaning and finishing waste, wood preserving waste, metal etching, and pesticides. The volatile organic chemicals (VOCs) with the highest concentrations in Zone A soils are mono-aromatics (primarily toluene and xylene) and ketones (primarily MIBK, MEK and acetone). These compounds are easily biodegradable either in the presence or absence of oxygen (i.e., aerobically or anaerobically). Lower concentrations of chlorinated VOCs (CVOCs) such as trichloroethene are also present, many of which are not biodegradable under aerobic conditions. The CVOCs are the main site constituents of concern found in groundwater.

An engineered cap was installed over Zone A in 2002 with subsequent cap maintenance performed in 2011 in response to differential settlement. The cap was compliant with the Model Toxics Control Act (MTCA). Soil vapor extraction, a technology well suited to remove VOCs, began in 1997 with up to five SVE wells being operated around the perimeter of Zone A. In 2010, the system was reconfigured to operate as a two-well system. To increase mass removal, the SVE system was reconfigured again in 2012 with two new well clusters, each with a shallow, intermediate, and deep well configuration, in a north-south alignment near the center portion of the Zone A unsaturated zone. A regenerative thermal oxidizer (RTO) was installed in 2015.

Past Performance

SVE has been extremely effective to date for removing mass (over 1,000,000 million pounds of VOCs removed) (Figure ES-1) and controlling groundwater impacts (a two mile long plume is now confined to an area immediately beneath Zone A).

From March 2012 to December 2013 the SVE system removed VOCs at a rate of approximately 220,000 pounds per year. However, two events occurred that led to a decision to temporarily suspend extraction from the high concentration intermediate units (i.e., extraction from VEW-6I and VEW-7I): 1) Potential indicators of subsurface combustion at municipal landfills were observed, in particular SVE well head extraction temperatures above 140°F and elevated carbon monoxide (CO); and 2) A combustion event was observed in the Balefill Area in late November 2013.

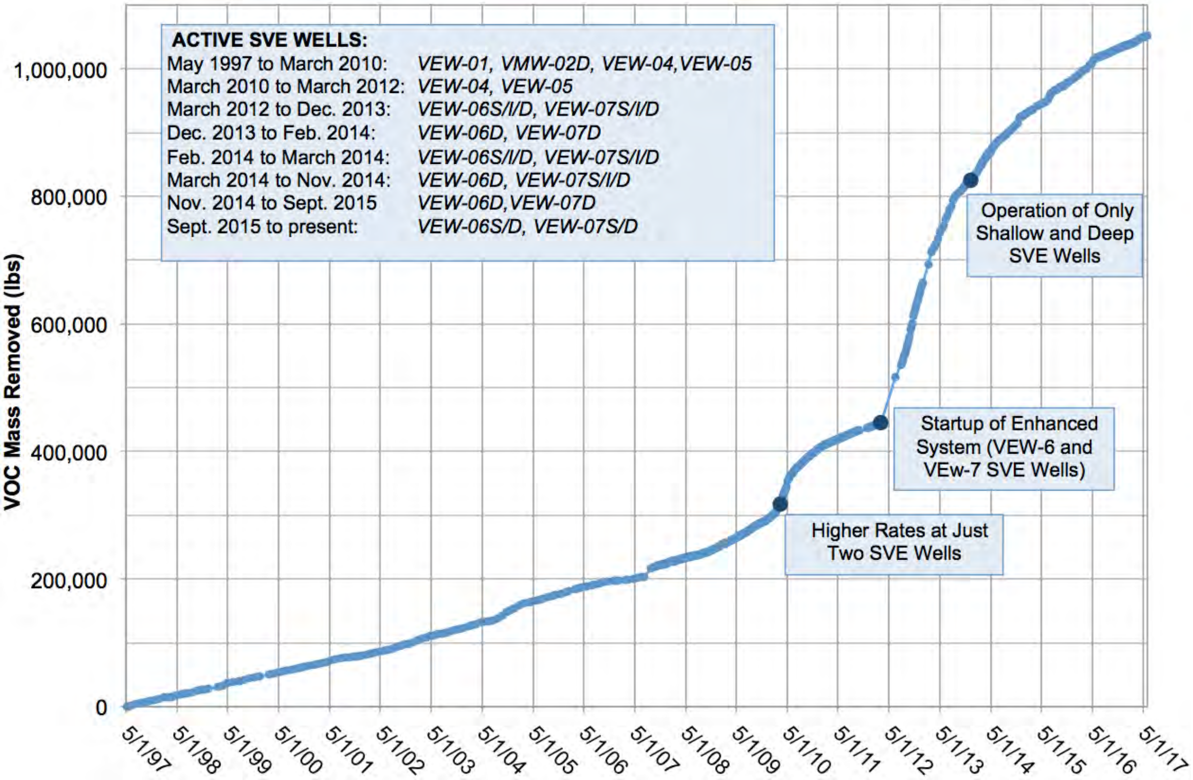


Figure ES-1. Zone A SVE mass removal of VOCs vs. time

Projections of Future Operations

- SVE can be safely operated in a more intensive manner than is currently being operated. Safe operation of the SVE wells in Zone A can occur at flows with up to a 200°F temperature in soil/water and up to 3,000 ppm CO measured in soil gas.

- SVE is the best, safest, and most efficient way to remediate Zone A. The estimated remediation time frame is 15 years from now.

- Excavation and other potential remedial technologies/actions are not appropriate for Zone A.

Conclusions

Extensive Zone A data conclusively demonstrate that combustion has not occurred since startup of the expanded SVE system, is not occurring presently, and is not expected to occur in the future. The parameters and their relationships supporting this evaluation are well understood, as are the nature and characteristics of Zone A. Consequently, the SVE system can be operated in more intensive manner and represents the best, safest, and most efficient way to remediate Zone A.

1.0 OVERVIEW OF CONTAMINANTS OF CONCERN IN ZONE A SITE HISTORY

There are four areas within the Pasco Landfill site in which waste is managed (Figure 1.1):

- Municipal Landfill (accepted waste until 1993);
- New Waste landfill (closed in 2001)
- Balefill/Inert Waste/Burn Trench Disposal Area (accepted waste until 1990); and
- Industrial Waste Area comprised of Zones A (remediation is ongoing), B (drums removed in 2002, final cap in 2013), C/ D (capped in 2002), and E (capped in 2002).

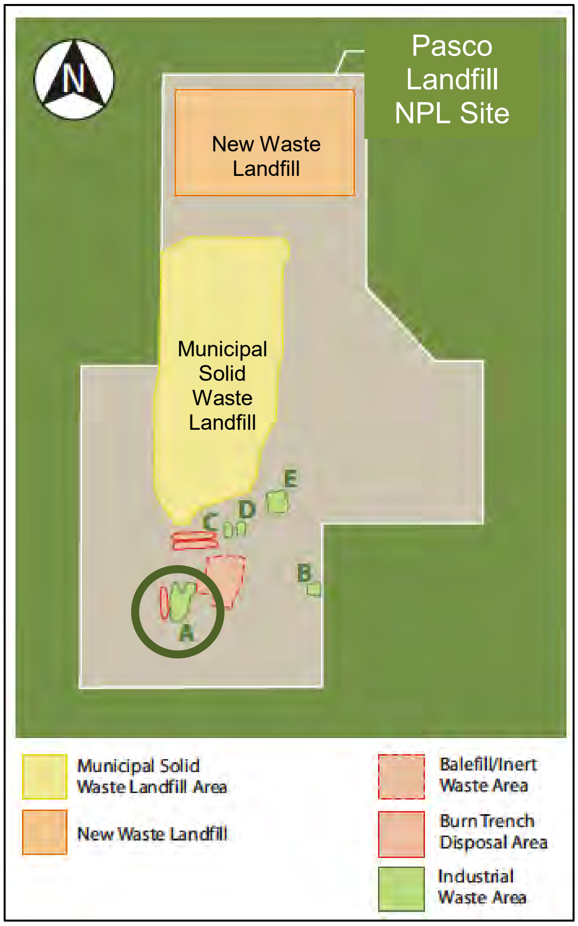


Figure 1.1. *Plan view of waste units. Zone A (green) is circled.*

Approximately 35,000 drums of industrial waste were disposed in Zone A between April 1972 and mid-1975. The drums contained a variety of chemicals including paint waste, metal cleaning and finishing waste, wood preserving waste, metal etching, and pesticides. Drums were initially placed randomly until about mid-1972, after which drums were stacked until mid-1975. Randomly placed drums likely lost a significant portion of their liquid fraction immediately upon placement. Stacked drums were placed four drums high and periodically covered with native soils. The Zone A cell was placed on reworked native soils, at least some of which appear to have included burned municipal waste (referred to as "Mixed Debris") from the former burn trench. A plan view map and geologic cross section of Zone A are shown in Figures 1.2 and 1.3.

1.1 Zone A Description

The volatile organic chemicals (VOCs) with the highest concentrations in Zone A soils are mono-aromatics (primarily toluene and xylene) and ketones (primarily MIBK, MEK and acetone). These compounds are easily biodegradable either aerobically or anaerobically. Lower concentrations of chlorinated VOCs (CVOCs) such as trichloroethene (TCE) are also present, many of which are not aerobically biodegradable. The CVOCs are the main site constituents of concern found in groundwater.

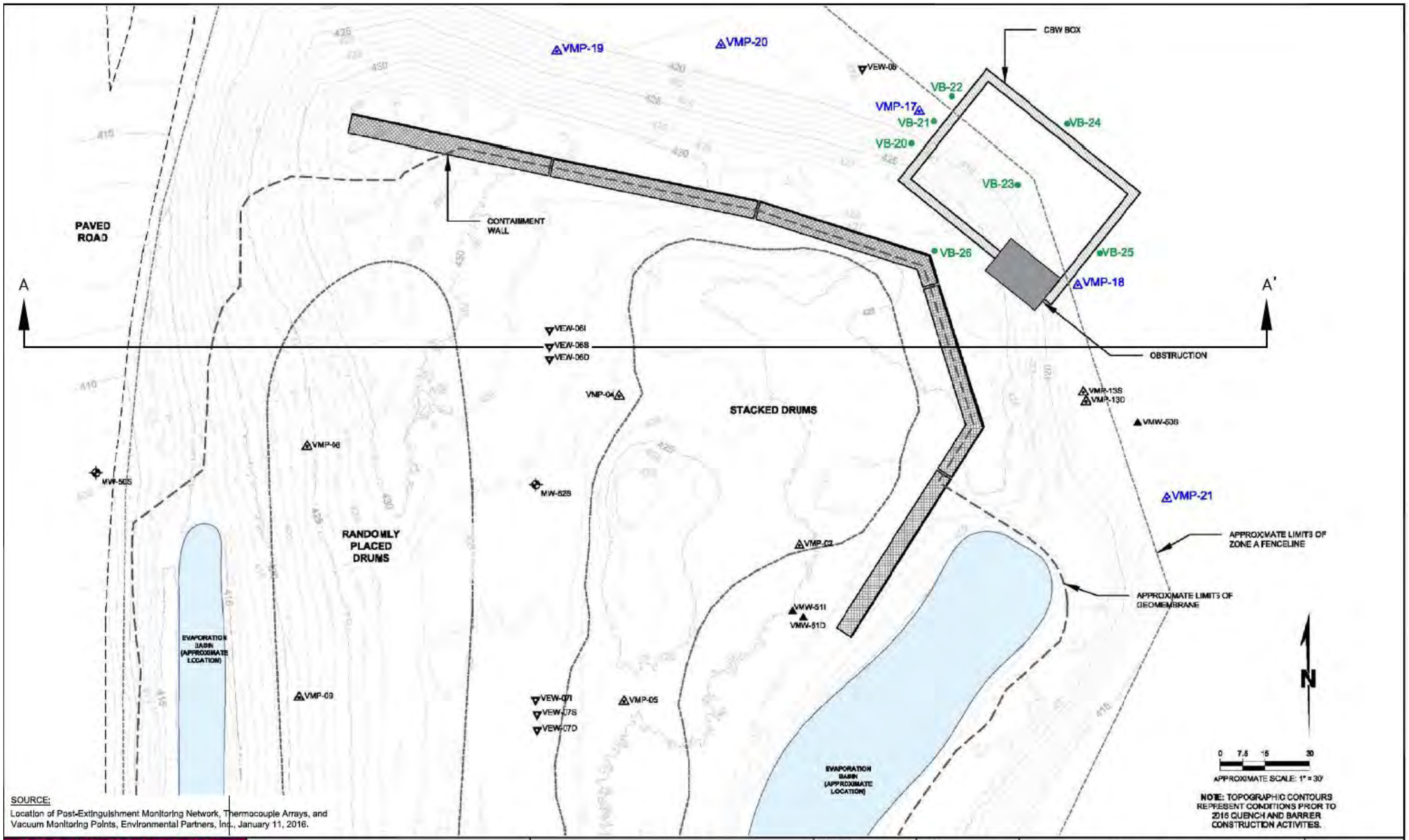
An engineered cap was installed over Zone A in 2002 with subsequent cap maintenance performed in 2011 in response to differential settlement. The cap was compliant with the Model Toxics Control Act (MTCA). Soil vapor extraction, a technology well suited to remove VOCs (see Appendix A) began in 1997 with up to five SVE wells being operated around the perimeter of Zone A. This system was reconfigured to a two-well system in 2010. To increase mass removal, the SVE system was reconfigured again in 2012 with two new well clusters, each with a shallow, intermediate, and deep well configuration, in a north-south alignment near the center portion of the Zone A unsaturated zone. A regenerative thermal oxidizer (RTO) was installed in 2015.

An estimate of the VOC mass in Zone A, based on number and volume of drums disposed, was developed as part of the Zone A Restoration Time Frame report (GSI/SCS, 2017a) (Table 1.1). One assumption in this mass balance approach is that much of the paint waste, the dominant type of liquid waste disposed, was comprised of still bottoms from solvent reclaimers that have an average of 25% volatile organics (USEPA, 1980).

The VOC-containing waste in the drums was in liquid form. Still bottoms from solvent reprocessing were "*kept sufficiently fluid so that they can be removed by pumping which simplifies handling and minimizes spills. Still bottoms are incinerated or sealed in drums for land disposal*" (USEPA, 1976). USEPA (1980) reported that "*a large majority of spent solvents and sludges are in the liquid form.*" Therefore, any failure of the Zone A drums holding VOC-containing waste would result in a release to the surrounding soil in Zone A.

Table 1.1. *VOC Mass Originally Disposed in Zone A (GSI/SCS, 2017a)*

	Most Likely Value	Middle 50% Range
Estimated VOC Mass	2,900,000 pounds	2,300,000 to 3,700,000 pounds



SOURCE:
Location of Post-Extinguishment Monitoring Network, Thermocouple Arrays, and Vacuum Monitoring Points, Environmental Partners, Inc., January 11, 2016.

NOTE: TOPOGRAPHIC CONTOURS REPRESENT CONDITIONS PRIOR TO 2015 QUENCH AND BARRIER CONSTRUCTION ACTIVITIES.

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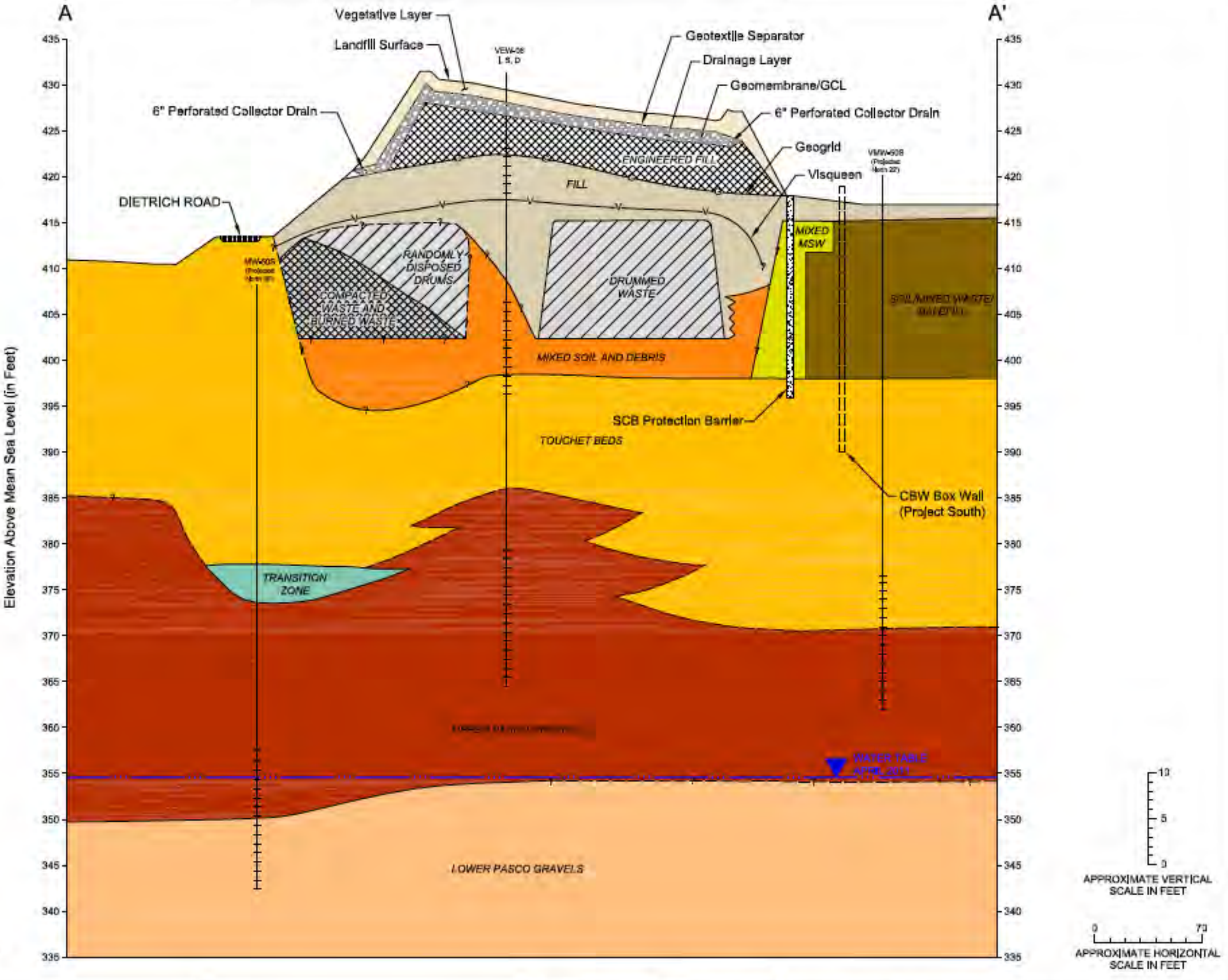
PROJECT NO. 04209046.04	DES BY EMS	ZONE A SITE PLAN	DATE AUGUST 2016
SCALE AS SHOWN	CHK BY JMR	TECHNICAL REVIEW OF PASCO LANDFILL ZONE A SOIL VAPOR EXTRACTION SYSTEM	Fig. 1.2
CAD FILE FIGURE 1	APP BY JJW		



SOURCE:

Location of Post-Extinguishment Monitoring Network, Thermocouple Arrays, and Vacuum Monitoring Points, Environmental Partners, Inc., January 11, 2016.

Figure 5.4.1-2, Draft Focused Feasibility Study, Pasco Landfill National Priorities List Site. Anchor QEA, LLC, September 2014.

Zone A Cover Replacement Details Sheet 1, Drawing No. D7, AECOM, August 6, 2015.

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PROJECT NO. 04209046.04	DES BY EMS	ZONE A CROSS SECTION	DATE AUGUST 2016
SCALE AS SHOWN	CHK BY JMR	TECHNICAL REVIEW OF PASCO LANDFILL	FIG **Fig. 1.3**
CAD FILE FIGURE 2	APP BY JJW	ZONE A SOIL VAPOR EXTRACTION SYSTEM	

1.2 Groundwater Status in 1996

After groundwater characterization was performed in the early-mid 1990s, a >2-mile long VOC plume was detected downgradient of the municipal landfill and Zone A (Figure 1.4). Key constituents were primarily CVOCs such as PCE; TCE; cis 1,2-DCE; vinyl chloride (VC); TCA; and 1,1-DCE. Current groundwater draft cleanup levels are shown in Table 1.2.

Table 1.2. *Current Draft Groundwater Cleanup Levels*

Compound	(ug/L)	Compound	(ug/L)
Trichloroethane	200	Tetrachloroethene	0.69
1-Dichloroethene	0.057	Toluene	615
2-Dichloroethane	0.38	Trichloroethene	2.5
2-Dichloroethene	16	Vinyl Chloride	0.069
Benzene	0.79	Total Chromium	100
MEK	5	Trichloroethane	200

Both the municipal landfill and Zone A were identified as sources of the groundwater plume. Concentrations above 100 micrograms per liter (ug/L) were observed near the sources, while off-site wells exhibited much lower concentrations. A groundwater recirculation treatment system (NOVOCs) was operated in Zone A groundwater from 2002 to 2008, but was then discontinued due to insufficient treatment effectiveness.

KEY POINTS

- In 1996, Zone A was unremediated with a large VOC mass in the vadose zone.
- A VOC plume more than two miles in length emanated from the Municipal Landfill and Zone A.

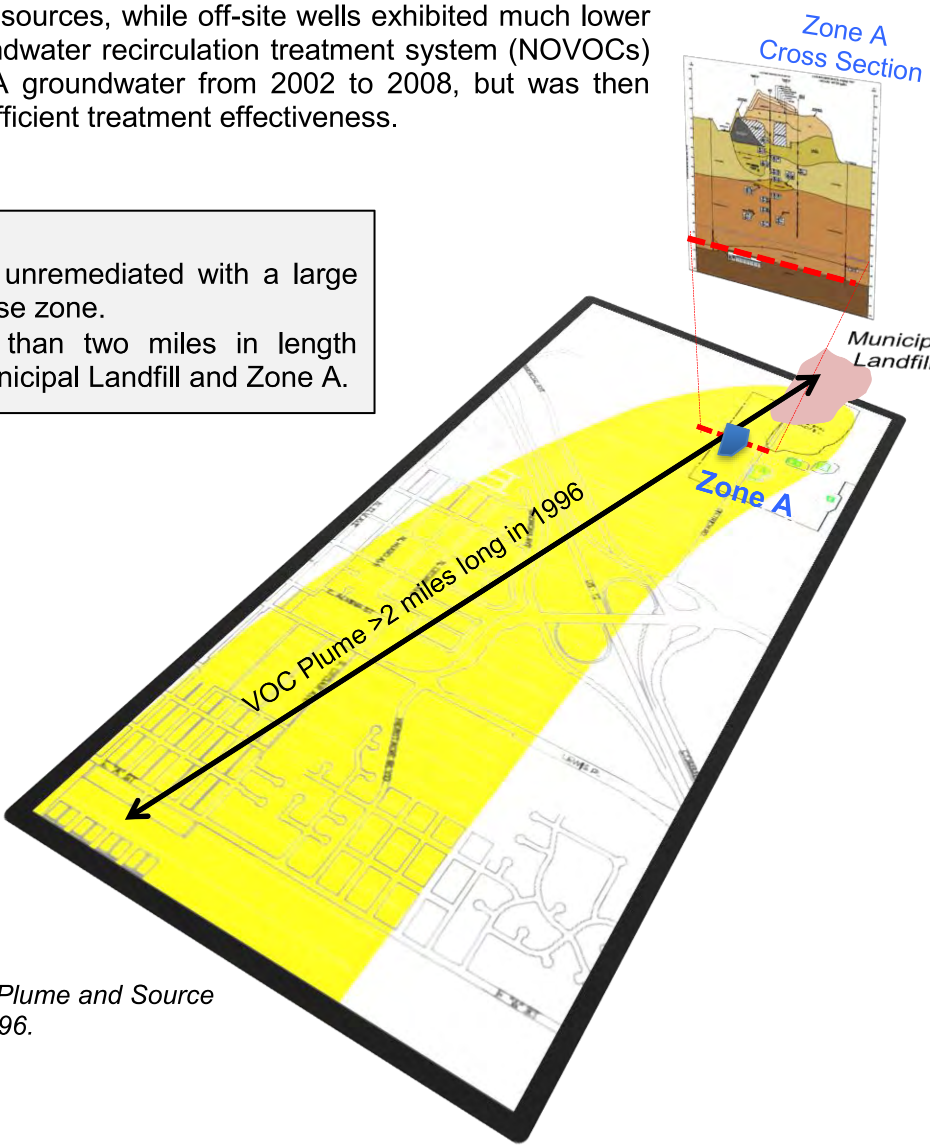


Figure 1.4. *Schematic of Plume and Source Zones in 1996.*

2.0 SVE HAS PROVEN TO BE AN EFFECTIVE MASS REMOVAL REMEDY AT ZONE A

2.1 Mass Removal – VOC Volatilization

From 1997 to 2012, the original perimeter SVE system removed 440,000 pounds of VOCs. Since the 2012 upgrade of the system to present, the SVE system removed an additional 610,000 pounds of VOCs. The cumulative amount removed from subsurface soils by the SVE system, ~1,050,000 pounds as of May 2017 (Figure 2.1), represents a highly effective level of performance for any in-situ remediation technology. Based on the mass balance estimate in the Restoration Time Frame report, almost one third of the estimated original VOC mass has been removed and destroyed by the SVE system alone. A more comprehensive mass balance including other mass removal mechanisms known to occur in such settings is presented below.

2.2 Mass Removal – Tentatively Identified Compounds (TICs)

Additional mass has likely been removed by the extraction of Tentatively Identified Compounds (TICs) in the SVE offgas stream that are measured by the analytical sampling but not included in the final VOC accounting. While the data suggests that TICs may represent the removal of an additional 30-50% of the VOC removal rate in the SVE offgas, the Zone A Restoration Time Frame report (GSI/SCS, 2017a) applied a conservatively small increase in the overall removal rate (most likely value 10% additional organic mass removed) to account for the TICs.

2.3 Mass Removal – Biodegradation

In addition, biodegradation of the VOCs has been ongoing since the liquid chemicals in the drums were first released to the subsurface. Recently, there has been intensive research in the field of Natural Source Zone Depletion (NSZD) that shows that Light Non-Aqueous Phase Liquid (LNAPL) bodies in petroleum hydrocarbon source zones naturally degrade at a rate of 100s to 1000s gallons per acre per year (Garg et al., 2017). Assuming that about an acre of Zone A (conservatively small area for this calculation) was subject to NSZD processes from 1975 to 2012 at a typical rate of 700 gallons of hydrocarbon biodegradation per acre per year (Palaia, 2016), then there likely has been 190,000 pounds or more of biodegradation prior to 2012. Biodegradation in Zone A prior to 2012 is supported by:

1) The highly biodegradable nature of the VOCs in both aerobic and anaerobic soil environments (GSI/SCS, 2017a);
2) Data from the 1998 Remedial Investigation that led the authors to conclude: *"Analysis of soil-gas data reveals the presence of elevated concentrations of methane accompanied by depressed oxygen concentrations in the vadose zone surrounding Zone A, indicating that biological degradation of the waste is occurring";* and
3) Elevated temperatures observed in well EE-3, immediately downgradient of Zone A, in the early 2000s with groundwater temperatures approximately 5°C warmer than surrounding monitoring wells. This heat was likely generated by biodegradation of the site constituents in Zone A.

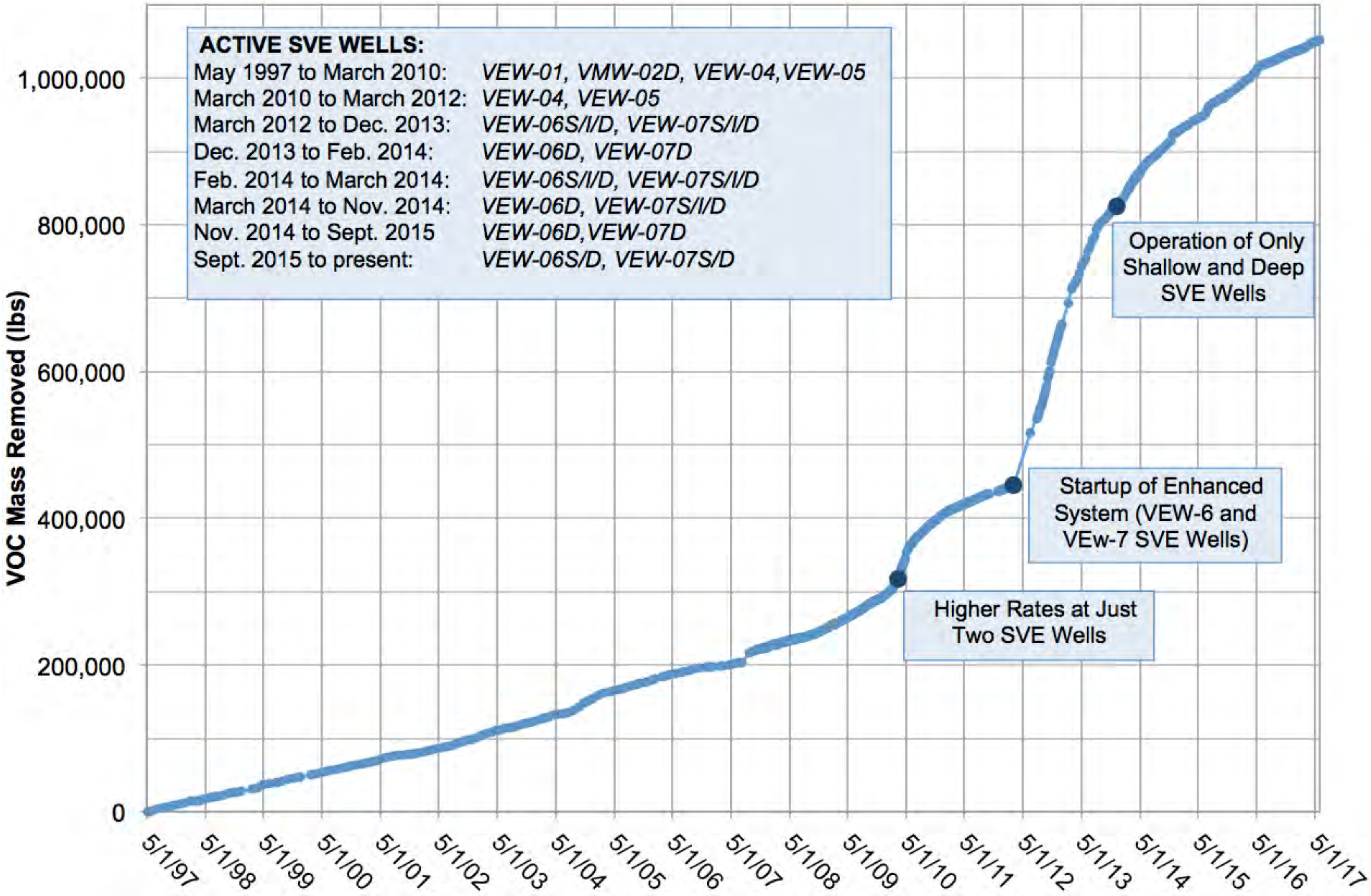


Figure 2.1. *VOC mass removed by SVE system from May 1997 to May 2017.*

Since 2012, when the upgraded SVE system was turned on, there has been even more biodegradation acting on the VOCs in the subsurface. GSI (2013) estimated that there was 50,000 to 190,000 pounds per year of aerobic biodegradation occurring from March 2012 to February 2013, compared to 244,000 pounds removed by the SVE system. This analysis used two independent lines of evidence, one based on oxygen consumption and one based on thermal methods, to measure the biodegradation. These data suggest that the overall VOC removal rate over the past few years was 44% higher than the VOC removal rate estimated assuming all the measured heat and oxygen consumption was caused by VOC biodegradation. After applying a conservative safety factor to the calculations, the Restoration Time Frame report (GSI/SCS, 2017a) accounted for the potential biodegradation that occurred from 2013 to May 2017, using a most likely value of ~55,000 pounds of VOCs biodegraded per year in Zone A.

2.4 Reduction in Vapor Concentration

One commonly used metric to evaluate the performance of an SVE system is the reduction in vapor concentrations over time. While the Zone A data are affected by the changing flowrates attributable to varying operating conditions over time, they still provide a good indication of the overall progress of remediation. The toluene vapor data (shown in Figure 2.2) were evaluated from March 2012 to May 2017. An estimated percent reduction in concentration was calculated by comparing median values from the initial and most recent years of operation of each of the six wells. More than half of the wells show a percent reduction in median concentration greater than 50%, providing evidence of significant mass removal. Overall, the general reduction in median vapor phase concentration supports the conclusion that a significant fraction of the original VOC mass, potentially half, has been removed by the SVE system as summarized on the next table. Note that these results are based on shorter records from the two intermediate wells, VEW-6I and VEW-7I, which have not been operated for about two years (see Combustion Evaluation Report, GSI/SCS 2017b).

2.5 Estimated Mass Removed

A statistical model of the Zone A VOC source mass removal since it was emplaced is presented in The Restoration Time Frame report (GSI/SCS, 2017a). The model generates a statistical distribution for key results; examples of key outputs are shown below.

Fraction of Total VOC Mass Removed to Date from Zone A by SVE System and Biodegradation
- Most Likely Value: 53%.
- 90% chance the value is equal to or greater than 36% of the initial VOC mass.

VOC Mass Removed to Date by SVE System and Biodegradation
- Most Likely Value: 1,500,000 pounds.
- 90% chance the value is equal to or less than 1,800,000 pounds.

VOC Mass Remaining in 2017
- Most Likely Value: 1,400,000 pounds.
- 90% chance the value is equal to or less than 2,650,000 pounds.

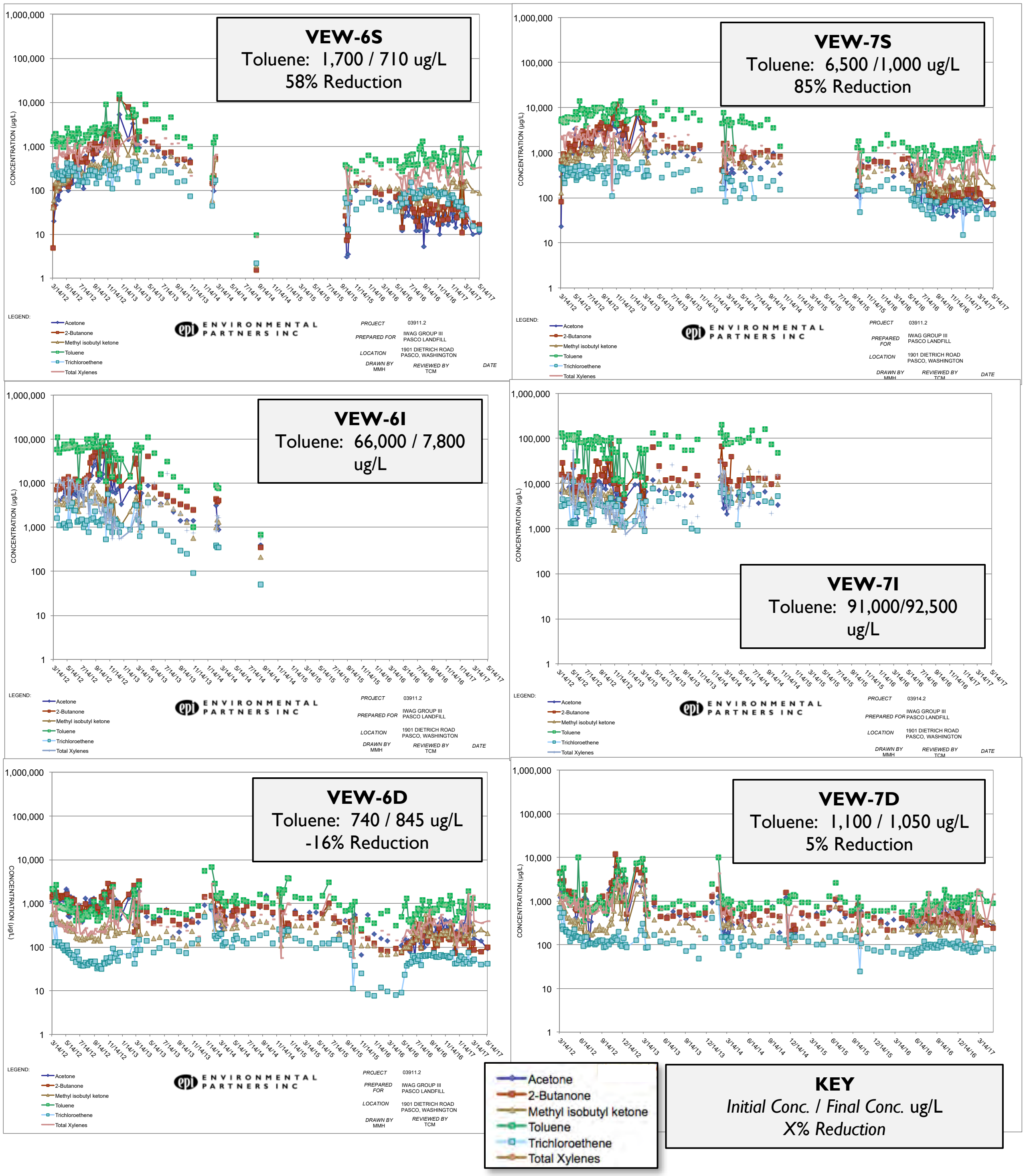


Figure 2.2. Vapor concentration vs. time at the six soil vapor extraction wells with vapor concentration on Y-axis (varying scales). Starting and ending median concentrations for toluene shown in each text box with corresponding percent reductions. For wells 6I and 7I, final concentration taken from fall 2014. Original figure: EPI.

KEY POINTS

- SVE has removed approximately 1,000,000 pounds of VOCs directly, or about one third of the original estimated VOC mass in place. In addition, the SVE system has also has removed TICs which increases the overall mass removed by the SVE system.
- Biodegradation has also removed significant mass: an estimated 190,000 pounds of VOCs from 1975 to 2012 and a most likely value of about ~60,000 pounds per year while the expanded SVE system has been in operation.
- When the direct removal, TICs, and biodegradation were combined in a statistical model of the VOCs in Zone A (see the Zone A Restoration Time Frame report, GSI/SCS, 2017a), the model showed about 53% of the VOC mass has been removed to date and about 1,400,000 pounds of VOC remain. The statistical model indicated that there is a 90% chance the remaining mass is less than 1,800,000 pounds.
- For the six SVE wells, there has been an average 56% reduction in soil vapor concentrations since the expanded SVE system went into operation in 2012. This supports the conclusion that about half the VOC mass has been removed to date.

3.0 IDENTIFYING AND RESOLVING SVE SYSTEM OPERATIONAL ISSUES AT ZONE A

This section reviews operational issues associated with the enhanced SVE system since operation commenced in 2012. A detailed review of the baled and loose municipal waste (Balefill Area) immediately adjoining Zone A is provided below in Section 4.

3.1 SVE Operational Issues at Zone A: Temperature and Carbon Monoxide

From March 2012 to December 2013 the SVE system removed VOCs at a rate of approximately 220,000 pounds per year. However, two events occurred that led to a decision to temporarily suspend extraction from the high concentration intermediate units (i.e., extraction from VEW-6I and VEW-7I):

1) Potential indicators of subsurface combustion at municipal landfills were observed, in particular SVE well head extraction temperatures above 140°F and elevated CO. These factors are discussed below as part of Section 4.
2) A combustion event was observed in the Balefill Area in late November 2013. This event is discussed in Section 5.

3.2 Lines of Evidence for No Previous or Current Subsurface Combustion in Zone A

There have been no previous and there are no ongoing subsurface combustion events in the Zone A area itself since drums were disposed there. The existing data are consistent with biological heating of the contaminants and bacterial biomass in Zone A.

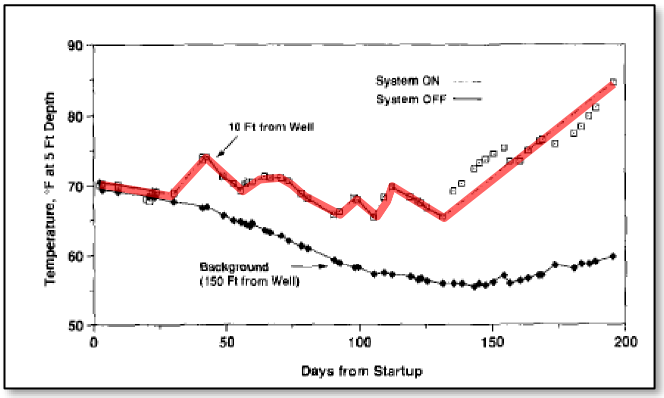
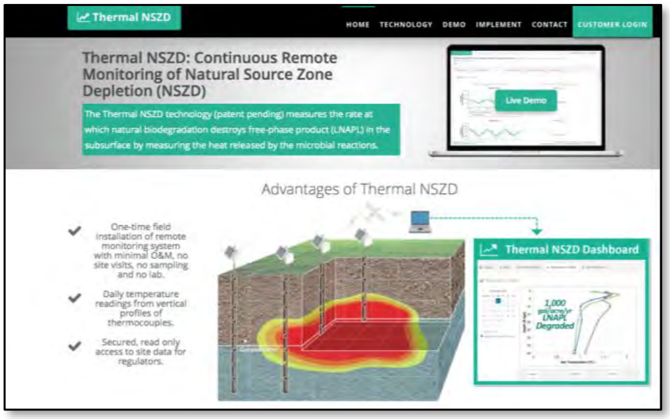


Figure 3.1. *Soil temperature increase due to operation of SVE system (best available graphic).*



Thermal NSZD: Continuous Remote Monitoring of Natural Source Zone Depletion (NSZD)

The Thermal NSZD technology (patent pending) measures the rate at which natural biodegradation destroys free-phase product (LNAPL) in the subsurface by measuring the heat released by the microbial reactions.

Advantages of Thermal NSZD

- ✓ One-time field installation of remote monitoring system with minimal O&M, no site visits, no sampling and no lab.
- ✓ Daily temperature readings from vertical profiles of thermocouples.
- ✓ Secured, read only access to site data for regulators.

Figure 3.2. *Thermal NSZD technology to measure biodegradation in subsurface by measuring heat (ThermalNSZD.com).*

Heat Generation. It has been well known since the mid-1990s that SVE can increase biodegradation and raise subsurface temperatures. Mohr and Merz (1995) observed heating from the SVE system as shown in Figure 3.1. Newell, in collaboration with Colorado State University researchers, is applying this well-known subsurface heating phenomena to measure NSZD rates (Figure 3.2). Thermal NSZD technology relies on the fact that combustion of gasoline liberates the same amount of heat as the biodegradation of a like amount of gasoline. The technology measures the increase in temperature in the subsurface and converts this to a rate of biodegradation sustained by subsurface bacteria.

High Temperatures. Bacteria can grow in high temperatures: *"[t]hermophiles, found in compost piles and other high-temperature environments, grow within the range of 40 to 75°C (105 to 165°F), with an optimum growth rate at 55 to 65°C (130 to 150°F)"* (Wastewater Biology, 1994). Jafari et al. (2017) assumed an upper boundary of anaerobic biological activity of 80°C (176°F). Zanetti (2008) reports that for aerobic municipal landfills: *"[t]emperature values during aerobic biodegradation are higher than during anaerobic one and they can reach 50-60°C (140°F). In some cases temperature can even reach 80°C (176°F) and the microbial activity is limited."*

While temperatures at 140°F are unusual at SVE sites, they are not uncommon in compost piles. Zone A was able to sustain such high temperatures because: 1) a large amount of biodegradable compounds, i.e., millions of pounds, were released and distributed throughout a large volume of soil; 2) the key constituents, such as toluene and acetone, are easily biodegraded by aerobic and anaerobic bacteria; 3) the soil around, below, and above the VOC containing zones in the Touchet Beds provide good insulation against heat loss; and 4) the cap eliminates infiltration and the cooling that infiltration provides. (Note Zone A was used as a burn area for municipal waste near the same time that the drums were disposed, so some burned material is described in core and bucket auger samples from Zone A (see the Combustion Evaluation Report, GSI/SCS 2017b).)

Overall, the scientific understanding of thermophilic bacteria and observations of Zone A temperature response both suggest a decrease in the rate of temperature increase above 140-150°F and the system establishing a thermal equilibrium around 160°F. Note that the highest observed temperature by the thermocouple monitoring system in Zone A was 159°F (GSI/SCS, 2017b).

*Carbon Monoxide***.** The initial scientific consensus was that CO in landfills above relatively low concentrations (e.g., 100 ppm) indicated that combustion was likely (e.g., see Appendix B for key excerpts). However, there has been a progressive transformation in the scientific community and the landfill industry regarding the mechanisms behind carbon monoxide generation. It is now well established that high concentrations of CO (up to 3,000 ppmv. Haarsted et al., 2006) can be generated from organic material without combustion. ATSDR (2002) reports that "typical landfill gas" can have CO concentrations up to 2,000 ppmv. Appendix B shows excerpts from key scientific studies regarding non-combustion generation of CO, and support the conclusion that the observed CO at Zone A was not generated by combustion.

3.3 Municipal Landfills Operated Safely at Higher Temperatures

While Zone A is much more like a non-landfill site than a landfill site (see next section), there is important information on how regulatory programs manage elevated temperature landfills. The U.S. Environmental Protection Agency's (USEPA) 1996 New Source Performance Standards (NSPS) for municipal solid waste (MSW) landfills address the issue of extracted gas temperatures in excess of 131°F or gas composition in excess of 5% oxygen. When those conditions occur, the USEPA allows for a Higher Operating Value (HOV) demonstration to be performed. Accordingly, landfill fires have not been identified as a concern and fires will not result from operation above those levels. When demonstrated, USEPA acknowledges that operations at these levels can be safe. Since 1996, the USEPA has approved hundreds of state and local air distraction HOV demonstrative projects with gas temperatures approved up to 200°F.

The NSPS HOV demonstration process does have some applicability to the operation of the SVE system at the adjacent and now closed Pasco Sanitary Landfill (Pasco). However, since a prescriptive protocol for HOV demonstrations does not exist, a detailed analysis of conditions based on both monitoring data and physical observations would be required to apply for or approve such HOV applications at Pasco. The following section describes why Zone A is much more like a non-landfill site than a landfill site.

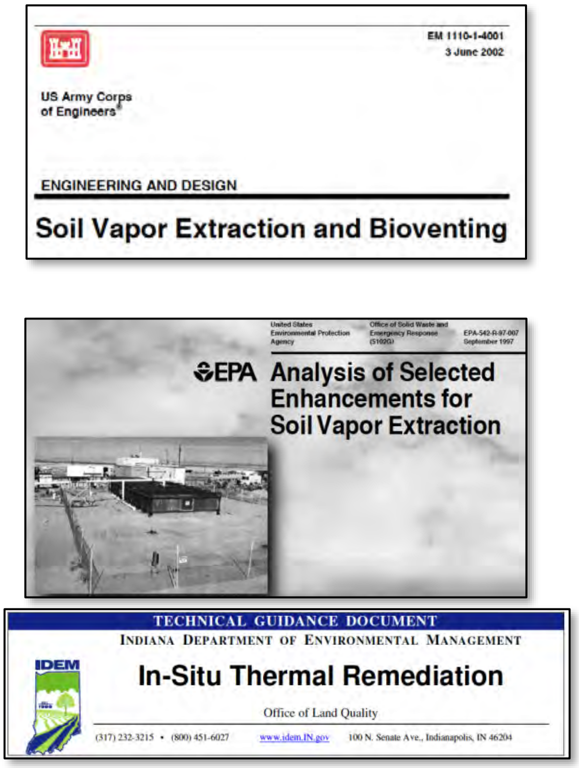
3.4 Lower Combustion Risk from Non-Landfill Sites

Non-landfill sites include thousands of hazardous waste remediation sites from the Underground Storage Tank, Resource Conservation and Recovery Act (RCRA), and Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) programs. In this respect, Zone A is much more similar to non-landfill sites than municipal landfills, (which provide the basis for most Federal Emergency Management Agency (FEMA) research and guidance), and, therefore, the municipal landfill combustion indicators can be misleading. In particular, the SVE and thermal industry design approaches and underlying guidance discussed below are much more relevant to Zone A than municipal landfill guidance documents (Figure 3.3, Appendix A):

Design Manuals. Standard practice for implementing SVE and thermal remediation technology at industrial sites does not include carefully monitoring soil gas temperature or carbon monoxide or comparisons to numerical limits. SVE design manuals do not mention air extraction temperature limitations or recommend measuring carbon monoxide to monitor the risk of combustion.

Thermal Enhancement for SVE. The risk of underground combustion is considered to be so low that there are numerous design manuals that instead recommend heating unsaturated soils to high temperatures (e.g., USEPA's "Analysis of Selected Enhancements for Soil Vapor Extraction"). One such project injected hot air at 350°F to enhance the performance of an SVE system.

*Thermal Remediation***.** Thermal remediation projects heat unsaturated soil at even higher temperatures. In-situ Thermal Desorption (ISTD) projects can reach temperatures of 1500°F (see Indiana Dept. of Environmental Management guidance).


EM 1110-1-4001
3 June 2002

US Army Corps of Engineers

ENGINEERING AND DESIGN

Soil Vapor Extraction and Bioventing

United States Environmental Protection Agency
Office of Solid Waste and Emergency Response (5102G)
EPA-542-R-97-007
September 1997

EPA

Analysis of Selected Enhancements for Soil Vapor Extraction

TECHNICAL GUIDANCE DOCUMENT
INDIANA DEPARTMENT OF ENVIRONMENTAL MANAGEMENT

IDEM

In-Situ Thermal Remediation

Office of Land Quality

(317) 232-3215 • (800) 451-6027 www.idem.IN.gov 100 N. Senate Ave., Indianapolis, IN 46204

Figure 3.3. *Key SVE guidance and related thermal technologies (see Appendix A).*

Smoldering Combustion Technology. An emerging technology is the STAR process where low-temperature (several hundred degrees F) smoldering combustion is initiated on purpose, with agency approvals, at contaminated sites for remediation. Savron, the company applying this technology, describes the equipment as:

> *"The above ground equipment used to implement the technology is similar to that used in Air Sparge (AS) / Soil Vapor Extraction (SVE) systems and includes compressors for sub-surface air delivery, blowers for ground surface vapor collection, and vapor phase activated carbon or a thermal oxidizer for vapor treatment. The specialized equipment associated with the STAR process includes the use of 2-inch diameter, carbon steel direct push ignition wells with a stainless steel screen, temporary in-well heaters to initiate the process, and subsurface multi-level thermocouple bundles to track the combustion process."*

Savron addresses the chance of a runaway reaction or explosion this way:

> *"What are the chances of generating a 'runaway' reaction or an explosion?*
> *None. Explosions are gas-phase combustion reactions involving gasified fuel and excess oxygen. STAR involves smoldering combustion that occurs on and within the surface of the fuel (i.e., the liquid contaminant). As such, its progress is dictated by the rate that oxygen can diffuse into the liquid and, thus, is necessarily oxygen-limited. Experiments have demonstrated that the rate of progress can be controlled by the rate of oxygen delivery up to a maximum and that further increases (i.e., excess oxygen) only cool (i.e., reduces) the reaction. Moreover, the radii of even the largest pores are below the critical length required for a flame to exist. Finally, experiments have repeatedly shown that when the air delivery is terminated, STAR stops immediately."*

To date, the Savron STAR technology has been implemented at sites in Virginia, New Jersey (two sites), Michigan, and Belgium (http://www.savronsolutions.com/case-studies).

Non-Landfill Sites vs. Landfill Sites.

The risk of combustion is a key national focus in managing municipal landfills. At industrial sites high temperatures are sometimes intentionally engineered in the unsaturated zone, and even the propagation of intentional combustion is considered an extremely low risk. The key distinguishing factor is the placement of hazardous waste material in the porous soil media at a Non-Landfill Site. In municipal landfills, the entire waste zone is a potential interconnected combustion source, while at industrial sites the contaminants are confined to the pore space of the porous soil media. When the contaminants are in a porous media, the risk of uncontrolled underground combustion of hazardous wastes becomes miniscule, so much that combustion is sometimes intentionally initiated to facilitate remediation.

The thermal remediation industry and agency regulators share the position that the risk of underground fires at sites with hazardous contaminants in porous media is negligible (Terratherm, 2001).

> *"The large amount of rock minerals absorbs reaction energy, so that even for a soil laden with 10,000 ppm THC (total hydrocarbons), complete combustion would raise the temperature to only about one-half of a flame temperature. To burn that much hydrocarbon would require hundreds of pore volumes of air. In practice, the amount of air present in the pore space of even a dry vadose zone is sufficient to burn only about 20 ppm of the THC, and that amount of combustion would raise the soil temperature only a few degrees. These are the reasons sand is used to extinguish fires."*

Zone A – Is a Non-Landfill Site. When risk from combustion is considered, Zone A should be considered a non-landfill, porous media site and not a municipal landfill. Figure 3.4 shows the continuum of risk from a porous media soil cleanup site (lowest risk) to a municipal landfill with exposure waste on the surface (highest risk). There are two factors at Zone A that increase the combustion risk, but only slightly:

1) Presence of some combustible material in the "mixed debris" layer; and
2) Potential that some drums are still filled with waste and/or voids are present in the Drum Fill and/or underlying material.

Both these issues are evaluated in detail in the Combustion Evaluation Report (GSI/SCS, 2017b). Overall, the report concludes that the "extensive Zone A data conclusively demonstrate that combustion has not occurred since startup of the expanded SVE system, is not occurring presently, and is not expected to occur in the future." Lines of evidence that do not support combustion are summarized below:

- Smoke and embers have not been observed in Zone A.
- Maximum in-situ temperatures recorded were 159°F during the main testing period.
- The observed CO_2/O_2 relationship indicates the primary oxidation reaction in most of Zone A is the biodegradation of organic chemicals, not the combustion or degradation of the mixed debris (e.g., wood, cardboard, and MSW-like material).
- The mixed debris was generally encountered in lenses separated by layers of silty sands and/or sandy silts with little to no organic content. There was little continuity in mixed debris in borings located only five feet apart.
- The average Total Volatile Solids (TVS) value of mixed debris in the large diameter borings is 11.4% and the average TVS value of all the large diameter borings in their entirety is 0.8%, based on the percentage of the material encountered. For comparison, MSW has a TVS content of 50%. The predominant portion of the fill within Zone A is soil that is not volatile; the portion that was initially volatile has largely decomposed and is no longer as combustible in any sense.

An evaluation of CO data showed that the highest laboratory measurement in the soil gas probes was 930 ppmv, and the highest recent laboratory CO from routine monitoring of the SVE extraction wells was 1,400 ppmv. However, potential combustion cannot be confirmed by this indicator alone. The elevated CO levels in the two intermediate SVE wells are from anaerobic biological sources as shown by a negative correlation to oxygen levels, cessation of regular well purging immediately before CO began increasing, a lack of smoke from these wells, and low oxygen levels (<2%) that likely cannot support combustion in the immediate vicinity of these wells.

Finally, autoignition of the vapor mixture was evaluated, and based on the technical literature for autoignition of gas mixtures, it is very unlikely that temperatures below several hundred degrees Fahrenheit will cause the organic vapors to autoignite. As part of the Combustion Evaluation analysis, a gas sample with both elevated vapor concentrations, the presence of carbon disulfide (a VOC compound with a relatively low autoignition temperature, see Appendix C), and the presence of oxygen will be subjected to a standard test (ASTM E659, Standard Test Method for Autoignition Temperature of Chemicals) to confirm that the autoignition temperature of the gas mixture is significantly higher than the expected maximum temperatures in Zone A.

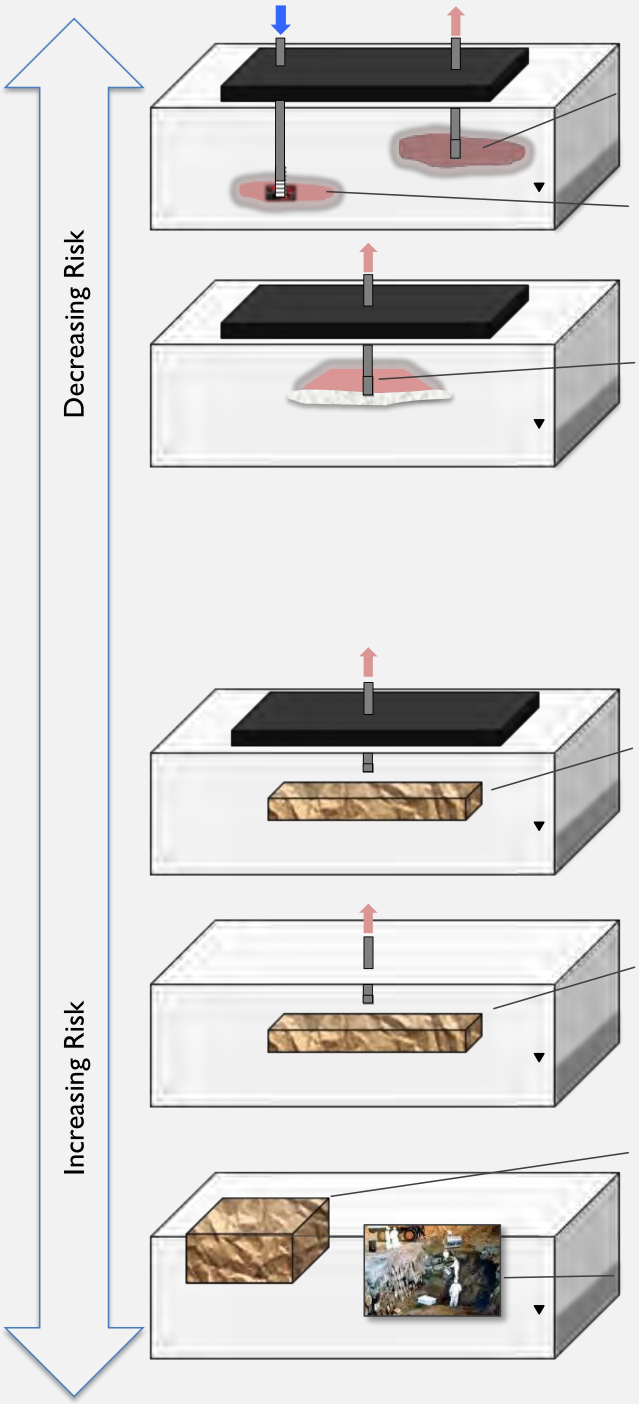


FIGURE 3.4. Relative Risk Associated With Different Conceptual Models To Have A Difficult-To-Control Combustion Event

Conceptual Model	Risk of Difficult-to-Control Combustion Event
1. Conventional SVE with contaminant liquids (NAPL) in porous media (sand/silt/gravel) and thermal remediation.	**Extremely Low Risk** Applied at 1000's sites; subsurface explosion/fire risk so small not mentioned in standard SVE Design manuals.
2. Intentional engineered / ignited in-situ combustion process (Star Technology)	**Extremely Low Risk** *"process becomes more robust and faces fewer technical challenges when applied in the vadose zone or capillary fringe."*
3. (ZONE A) SVE under cover and with partial vertical barrier wall with mixture of soil and generally thin and discontinuous lenses of mixed debris. All drums have experienced pitting failures that have released liquid contents and most drums have experienced structural failure (drum collapse).	**Very Low Risk** Presence of potential unburned debris increases risk but only slightly. The predominant portion of the fill within Zone A is soil and it is not volatile; the portion that was initially volatile has largely decomposed and is no longer as combustible in any sense.
4. Gas extraction under cap and over municipal waste.	**Low Risk** Because waste is continuous, not contained within a porous media, and can generate heat, solid combustion source landfill fires do occur (~8300 per year) but are easily controlled if there is a cap to cut off oxygen supply.
5. Gas extraction over municipal waste but with no cap	**Increased Risk vs. # 4.** Without cap, oxygen ingress is more difficult to control and engineering methods (gas addition, caps) may be required to extinguish any combustion event.
6. Near surface municipal waste without proper cover.	**Increased Risk vs. # 5.** Risk increases with waste near surface, but easily controlled and does not pose catastrophic risk
7. Excavation of high concentration drum fill area	**Unknown Risk** *"Unknown condition and state of drums, physical hazards, exposure during extensive segregation and handling of waste/soil and drum overpacking, and potential uncontrolled releases, pose significant risks to workers and potentially the community during excavation."* (planning may mitigate this but cannot eliminate risk)

3.5 Settlement

Some surface settlement is normal due to the collapse of metal drums; settlement at Zone A has been and will continue to be monitored carefully to ensure the integrity of the cap, as discussed in the Focused Feasibility Study (FFS). As described in the Restoration Time Frame report (GSI/SCS, 2017a), drum failure models developed at Los Alamos and Hanford National Laboratories predicted significant drum structural failures at Zone A would have started in the 2012-2014 time frame. This is when significant subsidence was observed at Zone A, thereby supporting the accuracy of the models and explaining the subsidence during this period (GSI/SCS, 2017a).

In the unlikely event that settlement becomes a concern then a contingency plan would promptly be implemented. Accordingly, there is no feasible scenario where surface settlement would occur at a level that would compromise the Zone A cap to the extent that it would result in the introduction of atmospheric oxygen in quantities necessary to establish a risk of combustion in the upper layers of Zone A:

> *SCS concluded that the differential settlement on the Zone A cap to date has resulted in total strain on the HDPE and geosynthetic clay liner (GCL) of between 0.9 and 3.5 percent. Those values are well below the allowable 10 percent yield elongation design basis, and are about two orders of magnitude less than the break elongation of the material necessary to suggest a strain-induced rupture of the HDPE geomembrane. SCS also concluded that the ultimate strain that the HDPE membrane is likely to receive as a result of foreseeable differential and cap-wide settlement is unlikely to result rupture of the HDPE membrane in the future.*

3.6 Regenerative Thermal Oxidizer (RTO) Issues

A Gulf Coast Environmental Systems (GCES) Regenerative Thermal Oxidizer (RTO) was installed in 2015 and started up in October 2015. A source test of the unit was performed in January 2016. The test results showed the unit was not meeting all of the air permit requirements. Further evaluation and testing of the RTO determined that the unit had not been built per the specification originally provided by the vendor, had been constructed with a damper system that was not capable of meeting the required destruction efficiency, and had a combustion temperature control system that could not prevent high outlet temperatures except on very low mass loading. GCES would not agree to address the identified problems.

To resolve these issues:

1) The specific problem with the RTO has been diagnosed;
2) A decision was made to replace the existing RTO with a new unit designed by Anguil; and
3) Steps are being taken to ensure compliance is being implemented.

Installation and operation of the replacement RTO unit will resolve the air permit exceedance issue.

KEY POINTS

- There have been no subsurface combustion events in Zone A since the SVE system was put in operation in 1997. The existing Zone A temperature and carbon monoxide data are all consistent with biological heating of the contaminants and bacterial biomass in Zone A:
  - Soil heating by bacteria is well known, as demonstrated by a new remediation approach (Thermal NSZD) built around detection of the heat generated by bacteria biodegrading petroleum hydrocarbons.
  - Non-combustion sources of carbon monoxide are common and known to produce concentrations currently observed in Zone A.
- Municipal landfills routinely operate at higher temperatures than those currently observed in Zone A.
- Non-landfill sites with contaminants in porous soil media have no temperature limitations for remediation purposes as shown by thermally enhanced SVE, thermal remediation, and engineered smoldering combustion projects. Uncontrolled combustion risk is exceptionally low at these sites.
- Zone A has characteristics much closer to a non-landfill, porous media site than a municipal waste landfill. The thin, discontinuous lenses of mixed debris increase the risk slightly, but overall, the risk of uncontrolled combustion at Zone A is very low. Less than 1% of the Zone A volume is comprised of burnable mixed waste; the vast majority of Zone A is comprised of soil.
- Based on the volatility of the mixed debris and the expected failure of drums after 2005, the observed settlement is likely due to drum collapse and is not a product of combustion.
- The RTO operational problems have been successfully diagnosed and a remedy will be in place soon. When this happens, the RTO will no longer be a limiting factor for future SVE operations.

4.0 OPERATIONAL RELATIONSHIP BETWEEN THE ZONE A SVE SYSTEM AND THE ADJACENT SOLID WASTE BALEFILL AREA

4.1 Background

The initiation and propagation of a subsurface landfill fire is complex and a function of many factors. These factors include waste composition, available oxygen, cover condition, and the existence of a gas collection and control system (GCCS).

In general, as a combustible material is heated, either through biological decomposition or chemical oxidation, ignition will occur at a given temperature, known as the ignition temperature of the material. The resulting heat of combustion will support a flame (or reaction) and propagation under most conditions. Combustion will continue until at least one of the following occurs:

(1) The combustible material is consumed.
(2) The oxidizing agent (typically atmospheric oxygen) is blocked and/or depleted.
(3) Heat acting as the ignition source is removed faster than it is produced.

Buried organic waste materials, containing primarily carbon and hydrogen, decompose either in the presence of oxygen (aerobic decomposition), or in the absence of oxygen (anaerobic decomposition), which releases heat in both processes. For most materials, the rate of biological decomposition is slow and anaerobic. The heat produced is transferred to the surrounding materials as it is formed and a stable, but somewhat elevated, temperature occurs as decomposition proceeds.

Spontaneous ignition (known as autoignition) of a combustible material can occur if enough air is available and higher temperatures exist to permit chemical oxidation. Under highly insulating conditions, the heat produced is retained, and the chemical oxidation rate continues to increase. Under these conditions, the combustible material may eventually reach its ignition temperature and spontaneous combustion occurs. The rate of heat generation, available air supply, and the insulating properties of the surrounding materials all influence whether chemical oxidation will result in temperatures reaching, and/or exceeding, ignition temperatures of the combustible material. Appendix A shows autoignition temperatures of the contaminants in Zone A.

Wastes placed in a landfill initially undergo aerobic biological decomposition, producing carbon dioxide (CO_2), water, and heat, which can result in maximum landfill temperatures in the 60° - 71°C (140° - 160°F) range. As available oxygen is consumed (and assuming a new source of oxygen is not available), biological decomposition becomes anaerobic, resulting in the production of methane (CH_4), CO_2, and heat. Temperatures will remain in the 60° - 71°C (140° - 160°F) range if the insulating properties of the waste materials are high. Increasing temperatures cause an increase in the rate of chemical oxidation of refuse, which initially occurs simultaneously with biological decomposition processes. This heating can continue past the limit of biological survival of the bacteria. Heating to the point of spontaneous combustion is the result of continued chemical oxidation, which follows the initial heat generated by biological decomposition. A continuous source of oxygen is necessary for this process to proceed to the point of ignition.

As temperatures within the landfill increase, the refuse material undergoes pyrolysis, i.e., chemical decomposition of matter through the action of heat in absence of oxygen. A continuous air supply that brings additional oxygen in contact with pyrolyzing refuse causes the material to become extremely hot. The heat generated is subsequently transferred to additional refuse materials, propagating the pyrolytic reaction. Heat from an elevated pyrolytic condition can continue to elevate, fail to release, and eventually reach the point of auto-ignition where combustion or fire occurs.

There have been some concerns expressed that temperatures of 160°F, or CO concentrations of 1,000 ppm may be an indication that combustion may be occurring, or that there is a high potential that one will develop. A discussion of the available guidance and literature on this subject follows.

First, the USEPA's New Source Performance Standards for MSW landfills were promulgated in 1996 and raise the issue of extracted gas temperatures in excess of 131°F, or gas composition in excess of 5 percent oxygen. When those conditions occur, USEPA allows for a HOV demonstration to be performed, to make the case that a landfill fire has not and will not be created as a result of operation above those levels. USEPA acknowledges that these levels can be safe. Note that since 1996, USEPA, through state air agencies or local air districts, has received and approved hundreds of HOV demonstrations, with allowable gas temperatures up to 200°F. These HOVs have been approved for both lined and unlined landfills.

It should be noted that there is no defined HOV protocol, neither in the rule nor in any of its supporting documents. Further, the USEPA has not provided a protocol or any specificity at all on how to perform a HOV demonstration. From experience with writing and reviewing successful HOV demonstrations in the past, we know that a combination of monitoring data and physical symptoms are typically used, and that no single indicator by itself is used as a basis to approve or deny a HOV demonstration. It takes a body of multiple indicators to determine approval or denial, usually utilizing both monitoring data and physical symptoms. Temperature and carbon monoxide readings alone are typically an insufficient basis for demonstration by themselves.

Second, an often-quoted reference on landfill fires is a FEMA document from 2002 entitled "*Landfill Fires - Their Magnitude, Characteristics, and Mitigation*." This document states that a landfill fire can be confirmed by the following:

1. Substantial settlement over a short period of time.
2. Smoke or smoldering odor emanating from the gas extraction system or landfill.
3. Elevated levels of CO in excess of 1,000 ppm.
4. Combustion residue in extraction wells or header piping.
5. Increase in gas temperatures in the gas extraction system above 140°F.
6. Temperatures in excess of 170°F.

The document does provide additional detail on CO levels, calling levels between 100 and 1,000 ppm suspicious of fire, and that even 10 to 100 ppm may be an indication of combustion. With that said, the FEMA document asserts that only CO readings above 1,000 ppm, along with several other indicators listed above, would provide the basis for a positive indication of a landfill fire.

Third, Ohio Environmental Protection Agency (OEPA) developed a guidance document on HOV demonstrations in 2010. This document advises that HOV demonstrations should be readily approved under the first tier of conditions, namely:

1. Landfill gas temperature at or above 150°F.
2. Landfill gas composed of no less than 45 percent methane.
3. Landfill gas containing no more than 1.5 percent oxygen.
4. Landfill gas with no more than 100 ppm CO.
5. Landfill gas with balance gas less than or equal to 8.5 percent.
6. Landfill gas with a ratio of percent methane to percent carbon dioxide in the landfill gas no less than 1.0.

It should be further noted that the levels above were set conservatively low, to allow easy and quick approval of such HOV demonstrations by OEPA and its various air districts as a first tier. The guidance specifically allows for HOV approvals on levels outside those set above, as part of a second tier process. OEPA states simply that such applications will be subject to a more comprehensive evaluation. Indeed, OEPA and the various Ohio air districts have approved many HOV demonstration applications under this second tier, at levels in excess of those identified above under its first tier.

It is a common misperception that CO is found in landfills only under conditions of active combustion or fire. The presence of CO in a landfill under non-combustion conditions has been well documented in the literature (Haarstad et al., 2006; Moqbel et al., 2010; Powell et al., 2006; Shaw Environmental, 2007; see excerpts in Appendix B). These studies clearly indicate the chemistry that causes CO to be generated under conditions of elevated temperature. Detailed data demonstrating this theory in the laboratory is provided in the studies. Waste samples were tested at bench-scale under conditions of applied elevated temperature. The result was CO concentrations at levels up to 3,000 ppm. Lastly, these studies also provide evidence of full-scale landfills with elevated CO readings in landfills clearly not undergoing combustion. Therefore, we conclude that CO may be an indication of landfill fire, but not exclusively so. Clearly, waste under somewhat elevated temperatures above 131°F also generates CO. Thus, if CO is to be used as an indicator of active landfill combustion, it should be used in combination with other monitoring data and physical observations, before any conclusion that combustion is occurring.

4.2 Past Combustion Events

According to the Balefill Combustion Causation Memorandum, (Anchor QEA, 2016) the Pasco Sanitary Landfill historically operated as a garbage burning facility and has experienced several surface and subsurface fire events over time. Public records and interviews with landfill operators indicate that these combustion events occurred from the late 1970’s to the mid 1980’s.

The most recent combustion event was first noticed in late November 2013, when an area of rapid subsidence occurred indicating a subsurface combustion event in the area. The surface deformation included an approximately 1-foot depression in the ground surface with surface cracking over an area of approximately 20 feet in diameter. As observed on December 3, 2013 by Mike Riley and John Richards and also noted in the *Balefill Area Interim Action Fire Suppression Work Plan* (June 2014), the depression and surface cracking were observed over an area where municipal solid waste had been disposed. On November 27, 2013, all SVE wells were operating and vapor emission from the cracks in the settlement area was observed (Jensen, 2013). Communication from Aspect Consulting to Ecology on December 2, 2013, stated that “there was smoke present in the depression and that it had a burning paper odor to it” (Bannister, 2013).

4.3 Contributing Factors to Recent Combustion Event

We believe that the primary factor contributing to the recent combustion event adjacent to Zone A is oxygen intrusion into the waste mass. The direct source of oxygen entering the waste mass is from ambient air, which is allowed to enter the waste due to the minimal and inadequate cover installed on the Balefill Area and adjacent municipal wastes. The Balefill Area cover has not been appropriately maintained since closure activities were completed in 1990. A network of en echelon surficial cracks has been observed (September 2012) in the cover material parallel to the top of the Balefill slope; the surface depression caused by the recent subsurface combustion event occurred near the end of one of these cracks in the Balefill Area cover (see Figure 2-9 of the *Balefill Area Interim Action Fire Suppression Work Plan*, June 2014) (see Figure 4.1).

Figure 4.1. *Echelon surficial cracks in Balefill Area.*

Fluctuations in barometric pressure act like a bellows introducing ambient air through the surface cracks into the waste mass. The barometric fluctuations are far greater in magnitude than any vacuum that could potentially be applied by the Zone A SVE system. The intermediate depth SVE wells in Zone A typically operated at vacuums between 3 and 24 inches of water column (in. W.C.) in VEW-06I and VEW-07I, respectively. These vacuums are recorded at the wellhead, as such the vacuum applied to the perforations of these wells is considered less due to pressure losses within the wells. In addition, because the geomembrane portion of the Zone A cover was not anchored at the toe of slope, the vacuum would likely have short circuited to atmosphere near the edge of the Zone A prior to inducing a vacuum beyond the limits of Zone A. Atmospheric barometric fluctuations were as large as 1 inch of mercury (13.6 in. W.C.) prior to observation of the subsurface combustion event in 2013 and are represented in the circled area of the following graph. These natural changes in pressure combined with the insufficient Balefill cover are far more likely to directly introduce oxygen into the Balefill waste area than the SVE wells. In this case the barometric change is about 1.6 inches of mercury or 21.8 in. W.C. over a period of about 6.5 days.

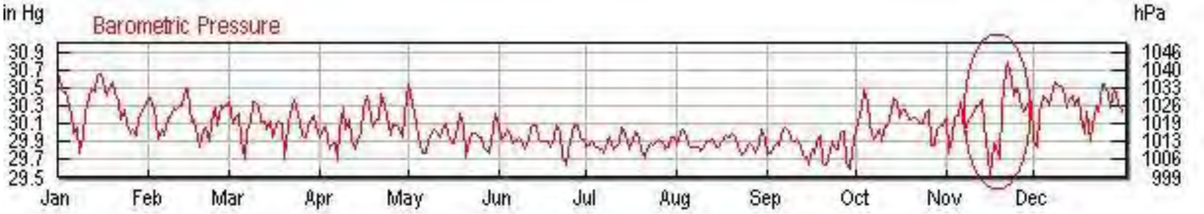


Figure 4.3. *Weather History for Pasco Airport (Station KPSC) – 2013, from www.wunderground.com*

Figure 4.3. *Weather History for Pasco Airport (Station KPSC) – November 2013, from www.wunderground.com*

4.4 SVE System Potential to Impact Balefill Area

The Zone A SVE system has a very low potential to induce a vacuum at the surface above the Balefill area. In order to transmit a vacuum to the Balefill surface, the vacuum applied to the SVE wells would have to be transmitted horizontally through the subsurface soils and then vertically up through the Balefill area to the ground surface. The shallow and intermediate SVE wells are installed in, or above the Touchet Beds formation and the deep SVE wells are installed below the Touchet Beds in the Upper Pasco Gravels formation.

The Touchet Beds formation that is located below Zone A is described as fine-grained glaciofluvial slack-water deposits that vary between 0 to 40 feet thick and consist of large quantities of gravel and fine sediment. The Touchet Beds are underlain by a poorly graded fine to medium sand material, which is considered to be the Upper Pasco Gravels of the Hanford Formation and are generally encountered at a depth of 40 feet below ground surface.

According to the air flow analysis that was completed in support of the Phase II Additional Interim Actions document, 100 percent Submittal Engineering Design Report for SVE System Upgrades (EPI, 2010); the Touchet Beds have a lower vertical and horizontal intrinsic permeability than the Upper Pasco Gravels.

The vertical permeability of the Touchet Beds is approximately 1-foot per day (ft/d) (~3.5×10^{-4} cm/sec) based on laboratory testing of soil samples completed during the Remedial Investigation phase and literature values. The permeability of the Upper Pasco Gravels were found to be approximately 1,200 ft/d (~4.2 x 10^{-1} cm/sec) from pump testing performed during Remedial Investigation work and is consistent with regional estimates of the Upper Pasco Gravel permeability values. The permeability of the Upper Pasco Gravels is about three orders of magnitude greater than that of the overlying Touchet Beds.

Additionally, the interface between the Touchet Beds and the Upper Pasco Gravels is abrupt and does not gradually change. The abrupt nature of the formation change, coupled with the drastic difference in permeability of the two layers allows the Touchet Beds to act as a confining layer above the Upper Pasco Gravels. Thus, the deep SVE wells that have screened intervals located in the Upper Pasco Gravels formation are likely to extract vapors exclusively from the Upper Pasco Gravels, regardless of what vacuum is applied. It is expected that the deep SVE wells zone of influence extends below the Balefill area in the Upper Pasco Gravels, with the zone of influence extending primarily in a horizontal fashion that it is unlikely to directly influence the Balefill as the Touchet Beds inhibit vertical distribution of vacuum into the Balefill material.

In October 2015, a minimum 3-foot wide soil-cement-bentonite protection barrier (SCB) was installed along the northern and eastern perimeter of Zone A. The base of the SCB was keyed into native soils a minimum of two feet. By keying the SCB into native soils, it allows the SCB to be in direct contact with the lower permeability Touchet Beds formation, thereby creating a continuous low permeability barrier between Zone A and the Balefill. The addition of the SCB further reduces the likelihood that the Zone A SVE system will transmit a vacuum beyond the extent of the barrier. Figure 1.1 provides a site plan of Zone A including monitoring point and barrier locations. A cross section is also presented as Figure 1.2 to further illustrate the vertical profile of the SVE system, SCB, and geological strata.

Subsurface soil gas pressures are influenced by fluctuations in barometric pressure. These fluctuations can induce a vacuum in subsurface soils with fluctuations generally more pronounced in shallower versus greater depths. The slight vacuum readings that have been observed at the monitoring points within the Balefill area could be attributed to these barometric pressure fluctuations.

However, to directly evaluate the effectiveness of the SCB at limiting SVE vacuum influence into the Balefill area, a vacuum monitoring system on both sides of the SCB should be established. By installing pressure monitoring points within close proximity and on both sides of the SCB an evaluation can be performed to determine if a direct correlation exists that shows vacuum from the SVE wells is reaching beyond the SCB. To effectively evaluate the SCB performance, the pressure monitoring points should be screened at the same elevation on both sides of the SCB. If higher vacuum is detected on the Zone A side of the SCB, but not on the Balefill side, one can deduce that the SVE system does not have an influence on the Balefill. This type of monitoring could prove that there is no SVE effect on the Balefill. In the unlikely circumstance that an effect is observed on the Balefill side monitoring probes, adjustments to the SVE vacuum can be adjusted to a level where little or no influence is detected.

The SCB vacuum monitoring system could consist of four sets of two probes with screen intervals installed at mid SCB depth and within 10 feet below the bottom of the SCB. The vacuum monitoring probes should be installed on both sides of the SCB and at a minimum of two locations along the length of the SCB. The shallow monitoring points will allow for monitoring for leaks within the SCB that the shallow SVE wells could potentially influence. The lower depth monitoring points will allow for evaluation of the extent of influence into the Touchet Beds below the SCB by the intermediate SVE wells.

KEY POINTS

- CO may be an indication of landfill fire, but not exclusively. Clearly, waste under somewhat elevated temperatures above 131°F also generates CO.
- If CO is to be used as an indicator of active landfill combustion, it should be used in combination with other monitoring data and physical observations, before concluding that combustion is occurring.
- No valid technical data has been presented that supports the conclusion that the SVE system has caused a combustion event within the Balefill Area
- The potential future influence of the SVE system on the Balefill Area will be further reduced with the recent installation of the vertical SCB between Zone A and the Balefill Area.
- The effectiveness of the SCB to prevent transmission of SVE vacuum from Zone A into the Balefill area will be monitored.

5.0 OPERATIONAL EFFECTIVENESS OF THE ZONE A SVE SYSTEM AT PROTECTING GROUNDWATER

The Enhanced Zone A SVE has had a striking effect on reducing groundwater impacts. From 1997 to 2002, the following interim actions were taken: installation of a perimeter-based SVE system, a NOVOCs groundwater recirculation remediation system, and placement of caps over Zone A and the MSW Landfill. By 2006, these measures reduced groundwater concentrations and the groundwater plume footprint compared to 1996 conditions (Figure 5.1). In March 2012, operation of the enhanced SVE system commenced and quickly led to more significant improvements in groundwater quality. As shown below, the downgradient plume collapsed to a small area immediately downgradient of Zone A and the MSW Landfill. By 2013 the plume had all but disappeared.

Figure 5.1. *Reduction in VOC concentrations in the off-property ground water plume through*

An analysis of groundwater data exceeding TCE draft Clean Up Levels (dCULs) was conducted to evaluate the performance of the pre-enhanced SVE system to the enhanced SVE system. First, monitoring wells were selected that had the longest continuous records before and after March 2012 when the enhanced SVE system went on-line. Three monitoring wells met these criteria: NVM-01, MW-12S, and MW-47S. Second, the total number of samples from the quarterly monitoring program were compiled to determine the number of exceedances and number of samples in compliance during the period of record. TCE was used as the critical parameter to evaluate the number of exceedances.

The results, shown on Figure 5.2, demonstrate that the enhanced SVE greatly improved groundwater quality (almost all samples meeting the dCUL) compared to the earlier, less effective system (almost all samples exceeding the dCUL).

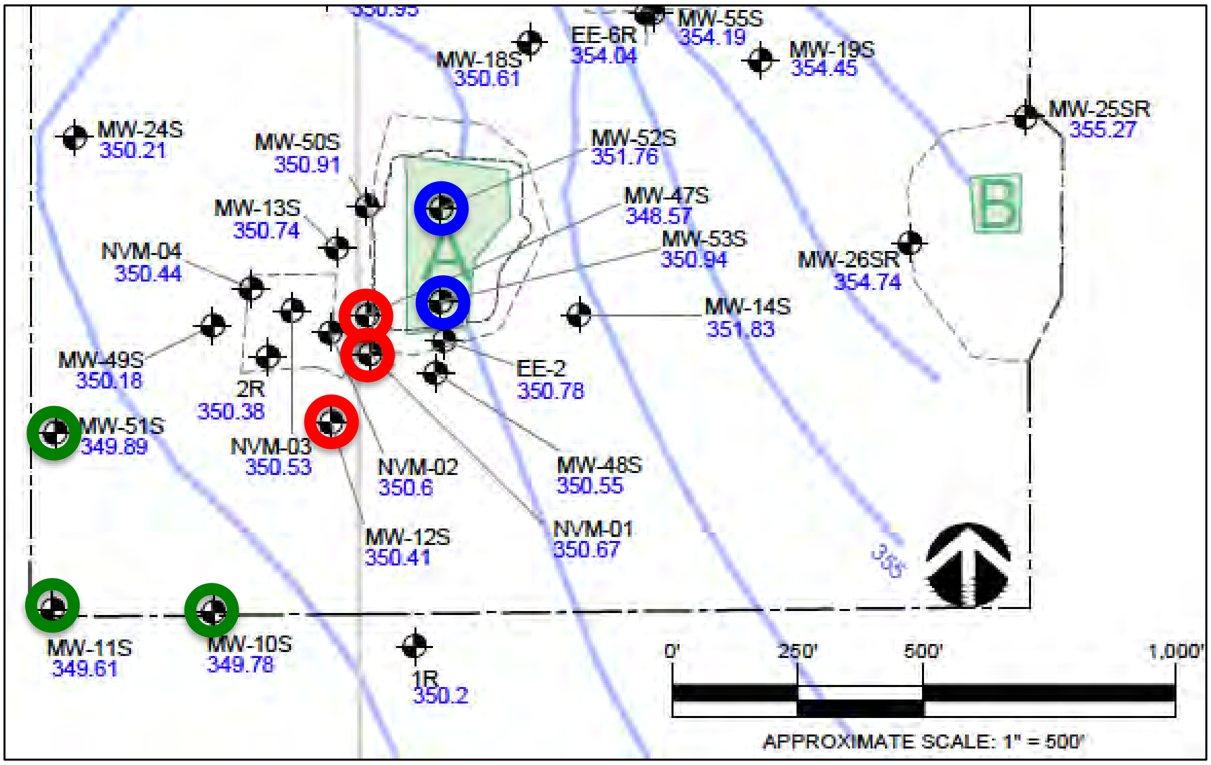


Figure 5.2. *Location map for monitoring wells used in Figures 5.3 (downgradient wells, red circles), Figure 5.4 (interior Zone A wells, blue circles), Figure 5.5 (Property Boundary wells, green circles)*

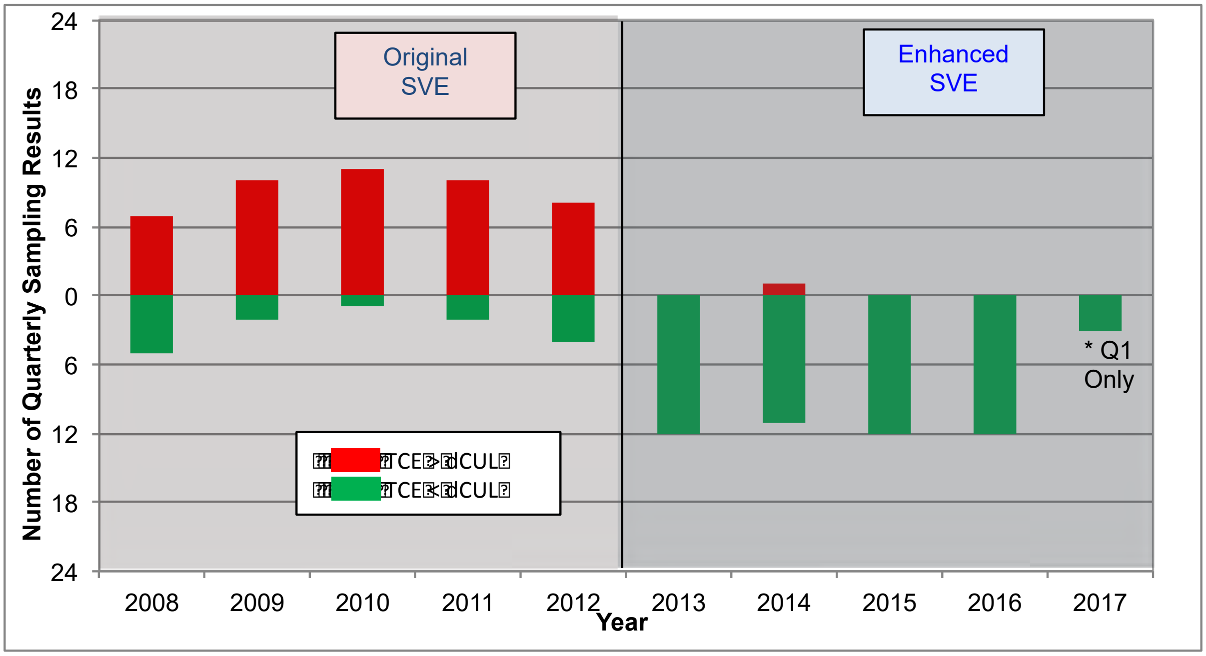


Figure 5.3. *Number of quarterly sampling results above (exceedance) and below (compliant) with the TCE dCUL of 2.5 ug/L for three downgradient Zone A monitoring wells: NV-01; MW-12S, and MW-47S. These three wells were selected as they were the only wells with consistent records from 2008 through 2017. Note 2017 shows only the first quarter of data.*

Next, an analysis of the change in TCE concentrations over time from January 2011 to January 2017 was performed for two wells in the interior of Zone A: MW-52S and MW-53S (Figure 5.2). Both figures show fluctuating TCE concentrations in groundwater in both monitoring wells since 2012. Because it is unlikely that these patterns were caused by new releases from drums (see the Combustion Evaluation Report, GSI/SCS, 2017b), change in the SVE operational pattern was evaluated as a possible cause.

Unexpectedly, it showed that a possible explanation of the fluctuating TCE concentrations in groundwater underlying the interior of Zone A may be operation of the SVE system in such a way that it draws vapors from the shallow/intermediate zones to the deep zones. As shown in Figure 5.4, there appears to be a correlation between the increases in TCE concentration (see blue lines) and changing the SVE flowrates where the deep well flowrates exceeded the combined shallow/intermediate well flowrates (dark red lines) (note that for much of this period, the intermediate wells were not operated, so in effect the “net deep flowrate” is the deep SVE well flowrate minus the shallow SVE flowrate at each location).

The physical mechanism may be that with a net deep flowrate at each location (locations 6 and 7), the deep wells drew warm TCE vapors deeper into the cooler subsurface where they condense. As shown in Figure 1.3, the shallow SVE wells have screens that extend to 11-15 feet below ground surface, the intermediate SVE wells to about 36 feet, and the deep wells to about 65 feet below ground surface. This mechanism is subtle and unexpected, as the original intent of running the deeper wells at higher flowrates was to intercept the vapors to reduce groundwater impacts.

If this hypothesis is correct, then resuming extraction from the intermediate zone may increase flow from the shallow/intermediate zone relative to the deep zone, resulting in much lower TCE concentrations in these two monitoring wells (MW-52S and MW-53S) and maintaining concentrations below dCULs. This hypothesis can be tested by temporarily changing the operational scheme to reduce the net deep airflow over a period of several months.

Finally, evaluation of the TCE concentration vs. time pattern for the three property-boundary wells immediately downgradient of Zone A (MW-10S, MW-11S, and MW-51S) shows these wells have never exceeded dCULs since 2011 (Figure 5.5). More importantly, these wells only show a small fraction of elevated TCE concentrations in the interior of Zone A (Figure 5.4), suggesting there is significant attenuation capacity in the aquifer between Zone A and these three property-boundary wells (distance of approximately 1,000 feet). This attenuation capacity, likely volatilization of TCE from the thin near-surface plume in groundwater to the vadose zone, may be sufficiently strong to be protective of groundwater at the property boundary under current conditions in Zone A without further operation of the SVE system.

A 6-month shutdown and rebound test, similar to ones performed at the Hanford Site (e.g., Brusseau et al., 2010), would increase the understanding of the attenuation capacity in the groundwater and the response to a SVE shutdown.

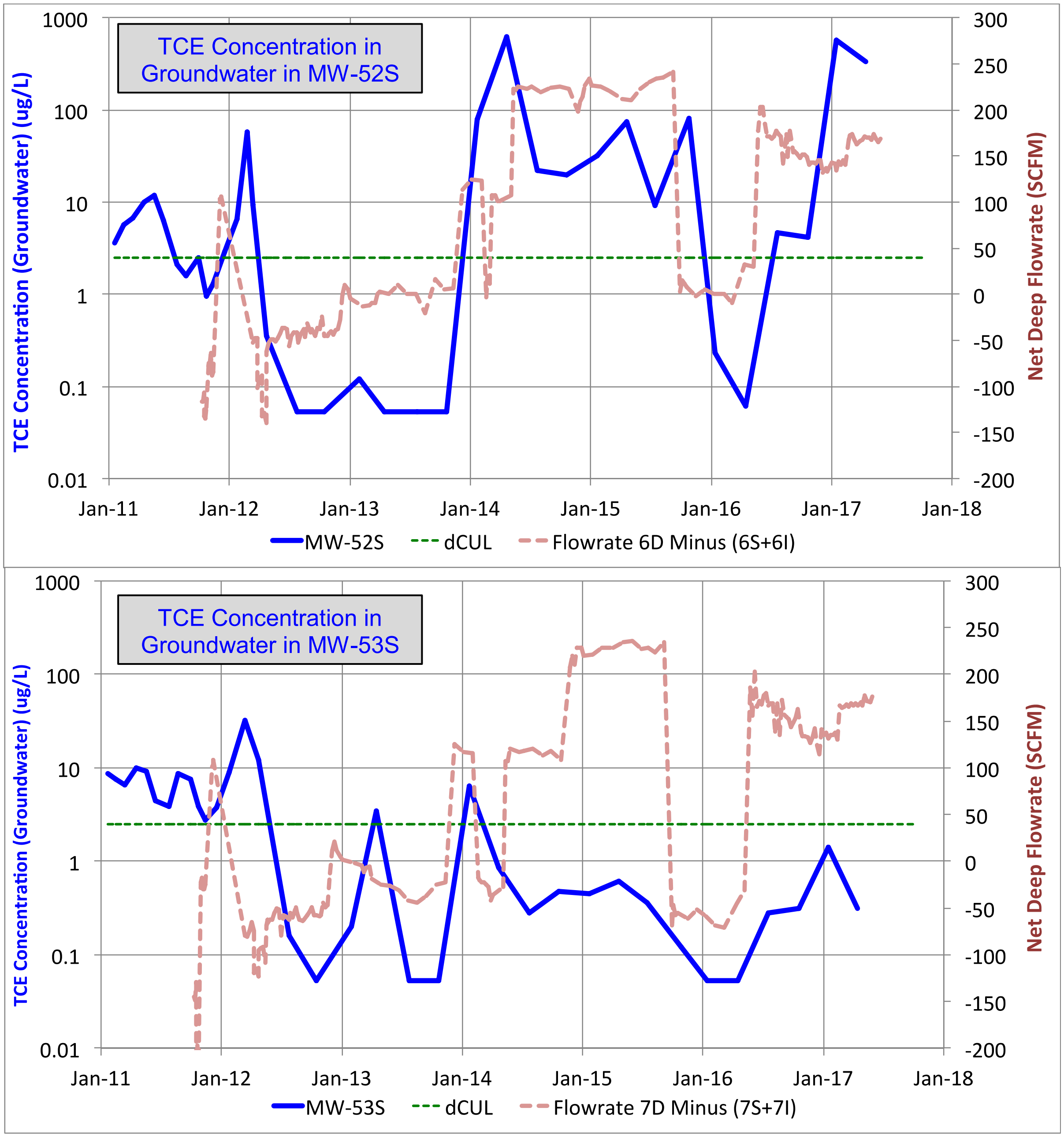


Figure 5.4. *Concentration vs. time for monitoring wells MW-52S (top panel) and MW-53S (bottom panel). MW-52S has exhibited a fluctuating pattern in groundwater concentration since 2012. This may be caused by an unexpected side effect of operating the SVE wells with more flow being extracted from the deep unit vs. shallow/intermediate units. There is a similar but much weaker pattern observed at monitoring well MW-53S, but with no exceedances of the dCUL for TCE since early 2014.*

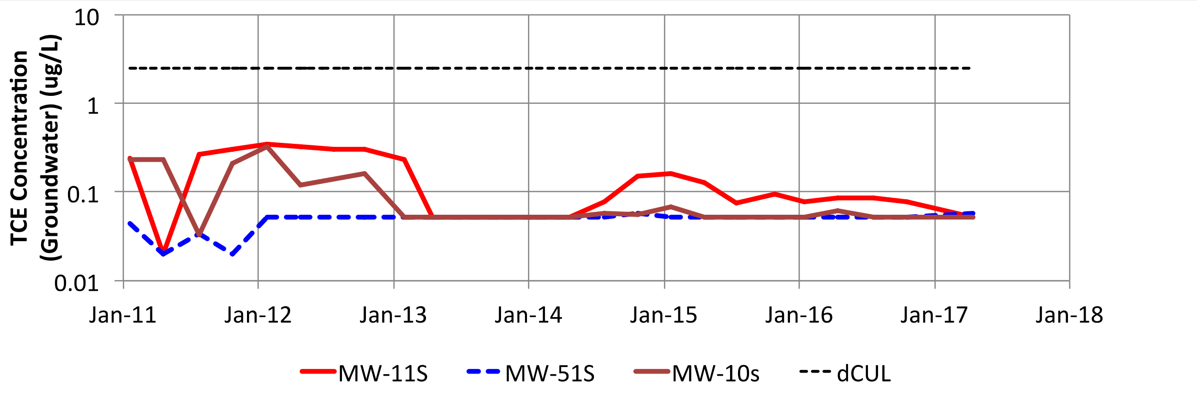


Figure 5.5. *Concentration vs. time for three off-property monitoring wells immediately downgradient of Zone A: MW-10S, MW-11S, and MW-51S. These wells have never exceeded dCULs since 2011 and do not show the effect of the fluctuating TCE concentrations in the interior of Zone A (see Figure 5.4).*

KEY POINTS

- A subset of the groundwater monitoring wells was selected to evaluate the impact of the enhanced SVE system on one key constituent, TCE.
- The enhanced SVE system had a dramatic effect on reducing TCE concentrations in three of the highest concentration Zone A wells.
- One unexpected result of operating the deep SVE wells at a higher rate than the shallow/intermediate SVE wells may be to draw warm VOC vapors deeper into the vadose zone where they condense. The fluctuating pattern in TCE concentrations in well MW-52S (and to a lesser extent in MW-53S) may be related to operating the deep SVE wells at relatively high rates.
- Three property-boundary wells showed little response to commissioning or changing operations of the enhanced SVE system, suggesting that there is significant attenuation capacity between Zone A and the property-boundary wells located ~1,000 feet downgradient. There is some chance that these downgradient monitoring wells would meet dCUL goals if the SVE system was turned off entirely. Further analysis, such as a 6-month shutdown and rebound test, similar to the ones performed at the Hanford Site, would increase our understanding of groundwater response to a SVE shutdown.

6.0 ONGOING OPERATIONS OF ZONE A SVE AND RESTORATION TIME FRAME

The Zone A Restoration Time Frame report (GSI/SCS, 2017a) was developed to estimate the restoration time frame over which the Zone A SVE system would have to operate to satisfy compliance requirements at the Pasco Sanitary Landfill. The key question, assumptions, and approach are summarized below.

6.1 Key Question

What is the restoration time frame for the Zone A SVE system should it be selected as the remediation technology in the final Cleanup Action Plan? In other words, how many years will the SVE system need to operate before the required cleanup levels at the points of compliance are achieved and the system can be shut down? (Note in Section 5, an analysis suggested that *Property Boundary monitoring wells* may maintain their compliance with the dCULs now even if the SVE system was permanently shut off. However, for the Restoration Time Frame report, the point of compliance was considered to be the *edge of the waste in Zone A.*)

What is Restoration Time Frame?

Restoration Time Frame is how many years the SVE system will need to operate before the required draft cleanup levels in groundwater are achieved and the system can be permanently shut down. At Zone A, the point of compliance is the *edge of the waste in the zone*. Restoration time frame is confirmed with *Rebound Testing* that shows if groundwater cleanup levels will permanently remain below their cleanup levels.

6.2 Key Assumptions

- It is assumed that the most likely operational scenario is one where the SVE system (shallow, intermediate, and deep vapor extraction wells) can be selectively operated without any material compromising effect of in-situ temperature or thermal oxidizer limitations starting in mid-2017. In particular, these likely mean being able to operate the intermediate wells, having the flexibility to change SVE flowrates, add SVE wells, and use new criteria for evaluating combustion that should supersede older combustion guidance (see the Combustion Evaluation report, GSI/SCS, 2017b). VOCs, in particular TCE, are the controlling constituents used as a proxy in this analysis for meeting dCULs in groundwater leaving the Zone A boundary.
- The source mass, soil vapor, and groundwater concentration are all linearly related.

6.3 Approach

Two approaches were used to determine key input data for the restoration time frame analysis - the time required for the drums to release flowable liquids and the percent contaminant mass that must be removed from the system to reach groundwater cleanup levels:

1. *Drum Failure Model:* A drum failure model, based on actual evaluation of the corrosion rate of drums emplaced in soils at the Hanford Site, was used to estimate the likely failure rate of the drums in Zone A over time.

2. *Percent Reduction Analysis:* Three methods were used to estimate the required percentage reduction in source mass to meet dCULs.

Then, two different methods and lines of evidence were used to estimate the restoration time frame, each with different working assumptions and criteria.

1. *Method 1 – Vapor Concentration Trend Method:* SVE system vapor concentration vs. time data were fit to a first order decay model to estimate the time required to reach dCULs.

2. *Method 2 – Box Model:* Data on the volume of waste emplaced in Zone A and a range of future SVE removal rates were used to develop statistically-based restoration time frames. Minimum, Most Likely, and Maximum values were estimated for seven key quantities used as input data for the Box Model.

6.4 Results

Key results of the analysis are:

- *Drum failure model:* All of the drums in Zone A most likely had pitting and corrosion failures by the year 2008, thereby releasing all or most of their liquid contents. In addition, all drums are predicted to experience structural failure by the year 2029, 12 years from now (2017). As a conservative measure, a five-year period was added to all the restoration time frame calculations to account for the possibility some drums have not released their contents as of 2017.

- *Three supporting calculations:* Between 90% and 99% of the source mass present in 2017 needs to be removed to meet the groundwater dCULs at the edge of the waste.

- *Method 2 Box Model:* About half the total VOC mass has been removed to date.

The restoration time frame going forward, assuming SVE operations will resume without the constraints imposed by the thermal oxidizer unit in 2017, are shown in Table 6.1.

Table 6.1*. Zone A SVE Restoration Time Frames*

Restoration Time Frame Method	Mostly Likely Restoration Time Frame:	90% Chance Restoration Time Frame is Less Than:
Method 1 Trend Method	14 Years	*not applicable*
Method 2 Box Model	16 Years	33 Years

- Restoration time frame Methods 1 and 2 use two very different approaches to estimate time frames. However, both methods provide similar results, increasing the reliability of the prediction.

- Rebound testing should be performed when the SVE system gets closer to its remediation goal as assessed during successive five-year reviews.

KEY POINTS

- A detailed Zone A Restoration Time Frame analysis report (GSI/SCS, 2017a) was developed using site data and several different methods to estimate how many years the SVE system will need to operate before the required dCULs in groundwater are achieved and the system can be permanently shut down. This analysis assumed the point of compliance is the *edge of the waste in the zone*.
- All of the drums in Zone A most likely had pitting and corrosion failures by the year 2008 thereby releasing all or most of their liquid contents. In addition, all drums are predicted to experience structural failure by the year 2029, 12 years from now (2017).
- Between 90% and 99% of the source mass present in 2017 needs to be removed to meet the groundwater dCULs at the edge of the waste.
- If the SVE shallow, intermediate, and deeps wells can be operated without any material compromising effect of in-situ temperature or thermal oxidizer limitations starting in mid-2017, then the SVE system would have to be operated for an additional ~15 years before the SVE can permanently be shut down.

7.0 SUMMARY OF REMEDIAL ALTERNATIVES TO SVE FOR REMOVING VOCS AND PROTECTING GROUNDWATER AT ZONE A

7.1 Excavation

There are multiple inherent challenges associated with potential excavation of the Zone A drums and underlying soils. The condition and integrity of the drums is unknown, they could be completely intact with no damage, damaged with active leakage occurring, or completely compromised with little to no remaining contents. Based on the amount of settlement observed in Zone A, it would appear that the latter is the case. The physical hazards associated with excavation include unstable trench or excavation, vapor release, and explosion.

The greatest physical hazards associated with excavation of the Zone A drums are the risks for a vapor release or explosion. These hazards are real and have been experienced during previous excavation work. According to a November 23, 2005 article published in The Spokesman-Review, work had to be stopped at the Idaho National Laboratory in eastern Idaho after a 55-gallon drum of hazardous waste exploded and started a small fire. Fortunately, no one was injured during the incident but it serves as a stark reminder of the risks associated with excavation and removal of drums with unknown contents. In a similar drum removal performed (in 2009?) at the Ephrata Landfill, several hundred drums were removed without incident. However, the Ephrata Landfill drums were placed after the drums in Zone A and the removal was performed before the drum collapse-induced settlement occurred within Zone A.

The potential for worker exposure to free liquids and vapors during extensive segregation and handling of waste/soil and drum over-packing is high. If over-packing is not possible, then roll-off containers with sealed lids will be required. Free liquids have the potential to further seep into the subsurface soils and adversely impact groundwater quality. The potential for uncontrolled releases poses significant risks to workers and the community during excavation.

Excavation activities may be negatively perceived by the public due to the potential exposure to workers, the adjacent community, and adjacent farmland. Transportation of the excavated materials to an off-site hazardous waste treatment, storage, and disposal facility creates additional exposure risks to workers, transporters, and the communities through which the materials travel.

In addition, a staging area will be required for temporary storage of the over-packed Zone A drums or roll-off containers and the underlying contaminated materials to determine the hazard category (HAZCAT) for disposal purposes. This staging area may be required to have a liner containment system similar to that required for a hazardous waste landfill (40 CFR 264). There is not a large enough area at the Pasco Landfill to efficiently stage the number of over-pack drums and volume of contaminated materials from Zone A and load onto transport trucks in an efficient manner.

In summary, according to Table 6.3.3-2 (MTCA Disproportionate Cost Analysis – Alternatives in Zone A from the Draft Focused Feasibility Study Report [Anchor QEA, September 2014]), the excavation alternatives (A-5 through A-7) are the most technically difficult to implement due to the complexity, uncertainty, and the magnitude of excavation activities. Additionally, these alternatives will require uniquely qualified personnel to properly complete the excavation.

Further, the administrative and regulatory requirements coupled with the overall coordination of the excavation alternatives will pose significant challenges; therefore, the excavation alternatives rank the lowest in the overall environmental benefit score and the benefit-to-cost ratio.

7.2 Bioventing

Bioventing is an in-situ remediation technology that uses microorganisms to biodegrade organic constituents adsorbed on soils in the unsaturated zone. Bioventing enhances the activity of indigenous bacteria and simulates the natural in-situ biodegradation of hydrocarbons in soil by inducing air or oxygen flow into the unsaturated zone and, if necessary, by adding nutrients. During bioventing, oxygen may be supplied through direct air injection into residual contamination in the soil. Bioventing primarily assists in the degradation of adsorbed fuel residuals, but also assists in the degradation of VOCs as vapors move slowly through biologically active soils. The rate of natural degradation is generally limited by the lack of oxygen and other electron acceptors rather than by the lack of nutrients. In conventional bioventing systems, oxygen is delivered to the treatment zone by a blower and subsurface wells.

Passive bioventing systems use natural air exchange to deliver oxygen to the subsurface via bioventing wells. A one-way valve, installed on a vent well allows air to enter the well when the pressure inside the well is lower than atmospheric pressure. When atmospheric pressure drops (due to a change in barometric pressure) below the subsurface pressure, the valve closes, trapping the air in the well and keeping the delivered oxygen in the soil surrounding the well.

There are several concerns and limitations to successful remediation via bioventing at Zone A, including:

- High soil moisture or low permeability soils reduce bioventing performance. Low temperatures may slow remediation. Extremely low soil moisture content may limit biodegradation and the effectiveness of bioventing.
- Vapors can build up in subsurface voids located within the radius of influence of the air-injection wells.
- Aerobic biodegradation of many chlorinated compounds may not be effective unless a cometabolite is present.
- Injected air travels through soils along the path of least resistance, thus resulting in zones that are not affected by the injected air stream.

7.3 Land Farming

Land farming is a bioremediation technology where contaminated soils are mixed with soil amendments such as bulking agents and nutrients, and then tilled into the ground. The material is periodically tilled for aeration. Contaminants are degraded, transformed, and immobilized by microbiological processes and by oxidation. Soil conditions are controlled to optimize the rate of contaminant degradation. Moisture content, frequency of aeration, and pH are all conditions that may be controlled. Land farming differs from composting in that it actually incorporates contaminated soil into uncontaminated soil.

There are multiple concerns and limitations to successful remediation via Land Farming at Zone A, including:

- The drums must first be removed and appropriately disposed of.
- A land farm must be managed properly to prevent both on-site and off-site problems with ground water, surface water, and air. The possible leaching of contaminants from the contaminated soil into the ground and groundwater is a concern.
- Liquids, runoff and leachate, resulting from the land farming process must be collected and treated at an on-site facility that must be constructed and monitored or shipped to an off-site treatment facility.
- Land farming incorporates contaminated soil into soil that is uncontaminated, creating a larger volume of contaminated material. Therefore, the rate at which contaminants are degraded must be balanced with the potential of creating a larger volume of contamination.
- Land farms must not be used to dilute contaminants. If it cannot be shown that biodegradation occurs for all contaminants of concern, land farming should not be used.
- Conditions affecting biological degradation of contaminants (e.g., temperature, and moisture) are largely uncontrolled, possibly increasing the time to complete remediation.
- Inorganic contaminants will not be biodegraded and may impact groundwater, but they may be immobilized.
- Since VOCs and SVOCs are present, off-gas (i.e., air emissions) control may be required.
- Dust control is an important consideration, especially during tilling operations.
- The depth of treatment is typically limited to the depth of achievable tilling (normally 18 inches). Since the contaminated soils are located below the Zone A drum fill, a large excavation beyond the extent of the drum fill would be required to successfully remediate the soils below Zone A.
- A large amount of space would be required to perform Land Farming of the contaminated soils.

7.4 Ex-Situ Thermal Desorption

Thermal desorption removes organic contaminants from excavated soil, sludge or sediment by heating them in a machine called a “thermal desorber” to evaporate the contaminants. Evaporation changes the contaminants into vapors (gases) and separates them from the solid material. Many organic contaminants can be removed by thermal desorption including VOCs and SVOCs. VOCs such as solvents and gasoline evaporate easily when heated. SVOCs require higher temperatures to evaporate and include diesel fuel, creosote (a wood preservative), coal tar, and several pesticides.

The desorber may be assembled at the site for on-site treatment, or the material may be loaded into trucks and transported to an off-site thermal desorption facility. To prepare the soil for treatment, large rocks or debris must first be removed or crushed. The smaller particle size allows heat to more easily and evenly separate contaminants from the solid material. If the material is very wet, the water may need to be removed to improve treatment. The water removed may require treatment using other methods.

The prepared soil is placed in the thermal desorber to be heated. Low-temperature thermal desorption is used to heat the solid material to 200° - 600ºF to treat VOC’s. If SVOC’s are present, then high-temperature thermal desorption is used to heat the soil to 600° - 1,000ºF.

There are several concerns and limitations to successful remediation via Thermal Desorption at Zone A, including:

- Vapors often require further treatment, such as removing dust particles. Organic vapors are usually destroyed using a thermal oxidizer.
- There is a potential for a lot of debris, including drums that must be crushed or removed to process the Zone A materials.
- Since the contaminated soils are located below the Zone A drum fill, a large excavation beyond the extent of the drum fill would be required to successfully remediate the soils below Zone A.
- A large amount of space would be required to install an on-site thermal desorption facility to treat the contaminated soils.

KEY POINTS

- SVE Technology is the best potential remedial action for Zone A.
- Excavation and other potential remedial technologies/actions are not appropriate for Zone A.

8.0 CONCLUSIONS

Extensive Zone A data conclusively demonstrate that combustion has not occurred since startup of the expanded SVE system, is not occurring presently, and is not expected to occur in the future. The parameters and their relationships supporting this evaluation are well understood, as are the nature and characteristics of Zone A. Consequently, the SVE system can be operated in more intensive manner and represents the best, safest, and most efficient way to remediate Zone A.

Our conclusion is based on the findings summarized below:

- The SVE system is a successful and efficient method to remove contaminant mass, with over 1,000,000 pounds of VOCs removed. When removal of tentatively identified compounds and biodegradation is included, it is likely that over half of the original mass of 2,900,000 pounds of VOCs has been removed.

- The SVE system has been successful in controlling the groundwater plume. Originally over two miles long, the plume exceeding dCULs is now confined within the Zone A footprint and does not extend beyond the edge of the waste (i.e., Dietrich Road) or to the property boundary. Concentrations in one well (MW-52S) have been fluctuating above the dCULs since expanded SVE operations started in March 2012, but this may be due to operational factors where high SVE flowrates in the deep extraction wells draw VOC vapors downward where they can affect groundwater.

- The elevated temperatures and carbon monoxide concentrations in Zone A are caused by: 1) the large amounts and readily biodegradable nature of the Zone A VOC contaminants; and 2) the insulating effects of the cap and the soil surrounding the contaminated zones.

- The extensive boring program shows Zone A has characteristics much closer to a non-landfill, porous media site than a municipal waste landfill. The mixed debris was generally encountered in lenses separated by layers of silty sands and/or sandy silts with little to no organic content. There was little continuity in mixed debris in borings located only five feet apart. The predominant portion of the fill within Zone A is soil that is not volatile; the portion that was initially volatile has largely decomposed and is no longer as combustible in any sense. Less than 1% of the Zone A volume is comprised of burnable mixed waste.

- All of the drums in Zone A most likely had pitting and corrosion failures by the year 2008 thereby releasing all or most of their liquid contents. In addition, all drums are predicted to experience structural failure by the year 2029, 12 years from now.

- If the SVE shallow, intermediate, and deeps wells can be operated without any material compromising effect of in-situ temperature or thermal oxidizer limitations starting in mid-2017, then the SVE system will likely have to be operated for an additional ~15 years before the SVE can permanently be shut down.

- Since we believe there is at most a low and managed risk of combustion within Zone A from operation of the SVE system in Zone A, the issue then becomes if a radius of influence (ROI) vacuum effect could reach all the way from the SVE wells under or through the barrier wall, to the Balefill, and thence to its surface in a significant enough way as to draw atmospheric oxygen into the Balefill and start a fire. There is low to no risk of this occurring. To ensure that the operation of the SVE wells comports with that determination, we have proposed a pressure-monitoring program that can detect any such ROI effects from the Zone A SVE wells to the adjacent Balefill area.

- The evaluation regarding alternative remedial actions that was completed as part of the draft Focused Feasibility Study determined that the excavation alternatives are the most technically difficult to implement due to their complexity, uncertainty, and magnitude of excavation activities. Additionally, the excavation alternatives ranked the lowest in overall environmental benefit and cost-to-benefit ratio. The draft Focused Feasibility Study concluded that the SVE system was the recommend alternative at that time and it still holds true.

- Based on the extensive site data and relevant technical literature, we believe that operation of the SVE wells at temperatures up to 200°F in soils/waste and 3,000 ppm CO in soil gas is appropriate and safe for Zone A.

KEY POINTS

- SVE has been extremely effective to date for removing mass (over 1,000,000 pounds of VOCs removed) and controlling groundwater impacts (a two-mile long plume is now confined to an area immediately below Zone A).
- SVE can be operated safely in a more intensive manner than is currently being operated now.
- SVE is the best, safest, and most efficient way to remediate Zone A. The estimated remediation timeframe is ~15 years from now.
- Excavation and other potential remedial technologies/actions are not appropriate for Zone A
- Safe operation of the SVE wells in Zone A can occur at flows with up to a 200 °F temperature in soils/waste and up to 3,000 ppm CO in soil gas.

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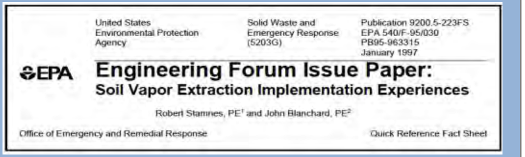
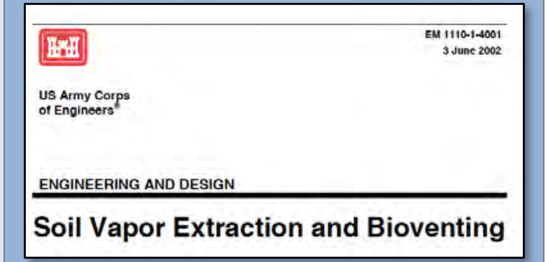
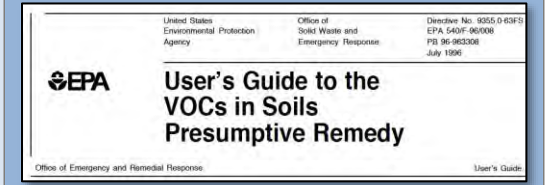
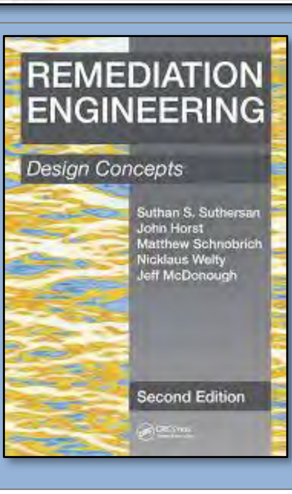
APPENDIX A: OVERVIEW OF SVE – KEY DESIGN MANUALS/GUIDANCE

Overview of SVE

Soil Vapor Extraction (SVE) is a well-understood, widely applied remediation technology for sites with VOCs in the unsaturated zone. There is a breadth of information in SVE Design Manuals, USEPA guidance, research papers, and other tools that explain when and how SVE should be applied at contaminated sites. The key references below support the selection of SVE for remediation of the VOCs in Zone A.

"Soil vapor extraction (SVE) is a commonly used technology for VOCs in soils that EPA has selected as a "presumptive remedy".	 United States Environmental Protection Agency Solid Waste and Emergency Response (5203G) Publication 9200.5-223FS EPA 540/F-95/030 PB95-963315 January 1997 EPA **Engineering Forum Issue Paper:** **Soil Vapor Extraction Implementation Experiences** Robert Stamnes, PE[1] and John Blanchard, PE[2] Office of Emergency and Remedial Response Quick Reference Fact Sheet
"In the United States, SVE is an accepted technology that has been used at landfill sites and at leaking UST sites since the 1970s. Soil venting, which includes air extraction and injection, is the primary method used in the United States to remove VOCs from the unsaturated subsurface." *"A majority (69 percent) of the total volume of soil at Superfund remediation actions is treated by SVE (USEPA 1999). The popularity and widespread use of venting is due to its simplicity of operation and proven ability to remove contaminant mass inexpensively compared to competing technologies."*	 EM 1110-1-4001 3 June 2002 US Army Corps of Engineers® ENGINEERING AND DESIGN **Soil Vapor Extraction and Bioventing**
"Once you have determined that your site is a candidate for a presumptive remedy, SVE should be analyzed first since it is the preferred presumptive remedial alternative. In most cases, SVE is extremely cost effective and can be implemented in-situ."	 United States Environmental Protection Agency Office of Solid Waste and Emergency Response Directive No. 9355.0-63FS EPA 540/F-96/008 PB 96-963308 July 1996 EPA **User's Guide to the VOCs in Soils Presumptive Remedy** Office of Emergency and Remedial Response User's Guide
"Soil vapor extraction (SVE) is an accepted, recognized, and cost-effective technology for remediating soils contaminated with volatile and semivolatile organic compounds. This technology is known in the industry by various other names, such as soil venting and vacuum extraction." • *SVE is an in-situ technology that can be implemented with minimum disturbance to site operations.* • *SVE is very effective in removing the volatile contaminant mass present in the vadose zone.* • *SVE has the potential for treating large volumes of soil at acceptable costs."*	 REMEDIATION ENGINEERING *Design Concepts* Suthan S. Suthersan John Horst Matthew Schnobrich Nicklaus Welty Jeff McDonough Second Edition

"The following two technologies are presented as innovative technologies that may be viable for hot spots at municipal landfill sites:

- *Vapor extraction*
- *In situ bioremediation*

SVE treatment may be particularly cost-effective for municipal landfills that will require landfill gas control, Once SVE treatment is completed, the wells can be used to collect or vent landfill gas."

United States
Environmental Protection
Agency

Office of Emergency
Remedial Response
Washington, DC 20460

EPA/540/P-91/001
February 1991

Superfund

EPA

Conducting Remedial Investigations/Feasibility Studies for CERCLA Municipal Landfill Sites

Widespread, Successful Use

Use of SVE is widespread, with over 1800 SVE systems being installed and operated in California alone (McHugh et al., 2013). There are several sites where SVE has successfully removed over one million pounds of contaminants, such as the Chevron Bakersfield Refinery (over eight million pounds removed), Kirtland AFB in New Mexico (three million pound removed), Davis-Monthan AFB in Arizona (1.3 million pounds removed), and McClellan AFB in California (one million pounds of contaminants removed by the site's SVE systems). This does not include a large number of thermal remediation sites where thermal heating is combined with SVE to remove volatile contaminants.

Commonly used SVE design manuals, guidance documents, and scientific papers based their decision logic on volatility and soil permeability. When the procedures in commonly used SVE Design Manuals (USCOE, 2002; USEPA, 1996; Suthersan, 2017) are applied to Zone A, all support the conclusion that SVE is an appropriate remediation technology to remove VOCs from the site.

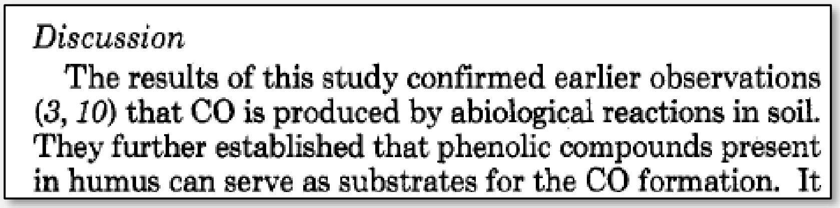
One guidance document (USEPA, 1991) addresses using SVE *within* municipal landfills, but states SVE can be used if health and safety precautions be taken if landfill gas is present. More importantly, none of the key SVE documents for petroleum and hydrocarbon sources recommend that SVE systems at petroleum/industrial sites need to be designed to control their systems to prevent subsurface combustion. While there are cautions about gas extraction at municipal landfills to prevent subsurface combustion, these cautions are not pertinent to conventional SVE systems at gas stations, refineries, chemical facilities, and hazardous waste sites.

APPENDIX B. EXCERPTS FROM RELEVANT TECHNICAL PAPERS

Non-Combustion Carbon Monoxide Generation in Nature

Conrad and Seller, 1985

Key Point: CO originates from non-combustion, abiotic reactions in soil.



Discussion

The results of this study confirmed earlier observations (*3, 10*) that CO is produced by abiological reactions in soil. They further established that phenolic compounds present in humus can serve as substrates for the CO formation. It

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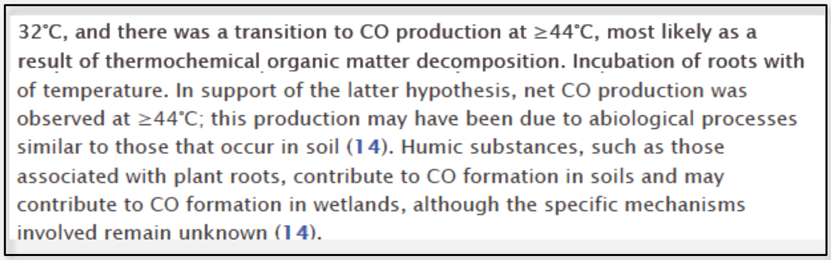
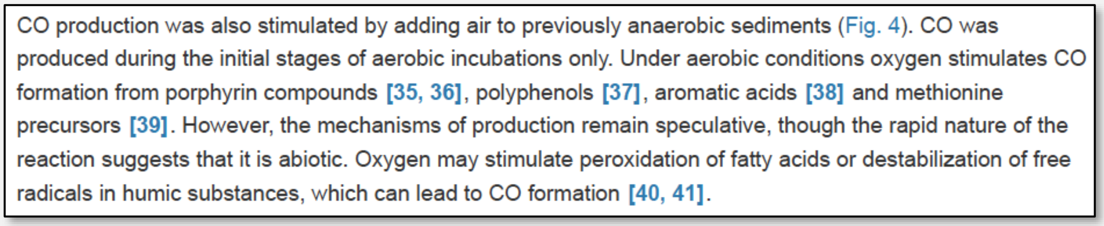
Rich and King, 1998

Key Point: CO is released from freshwater plants, particularly at temperatures greater than 44°C (112°F).



32°C, and there was a transition to CO production at ≥44°C, most likely as a result of thermochemical organic matter decomposition. Incubation of roots with of temperature. In support of the latter hypothesis, net CO production was observed at ≥44°C; this production may have been due to abiological processes similar to those that occur in soil (14). Humic substances, such as those associated with plant roots, contribute to CO formation in soils and may contribute to CO formation in wetlands, although the specific mechanisms involved remain unknown (14).



CO production was also stimulated by adding air to previously anaerobic sediments (Fig. 4). CO was produced during the initial stages of aerobic incubations only. Under aerobic conditions oxygen stimulates CO formation from porphyrin compounds [35, 36], polyphenols [37], aromatic acids [38] and methionine precursors [39]. However, the mechanisms of production remain speculative, though the rapid nature of the reaction suggests that it is abiotic. Oxygen may stimulate peroxidation of fatty acids or destabilization of free radicals in humic substances, which can lead to CO formation [40, 41].

Rich and King, 1999

Key Point: CO is generated by adding air to anaerobic sediments via oxidation of aromatic acids, fatty acids, and other compounds.

King, 2001.

Key Point: Dead biomass releases CO when heated to 40°C (104°F). CO concentrations up to 1000 pm were measured, the upper detection limit of their analytical equipment.
(This research is relevant because Zone A contains dead biomass from the aerobic bacteria that are continually dying and being replaced by new cells feeding on the VOCs).

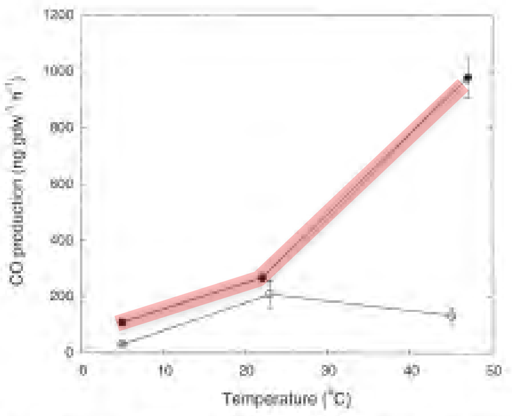
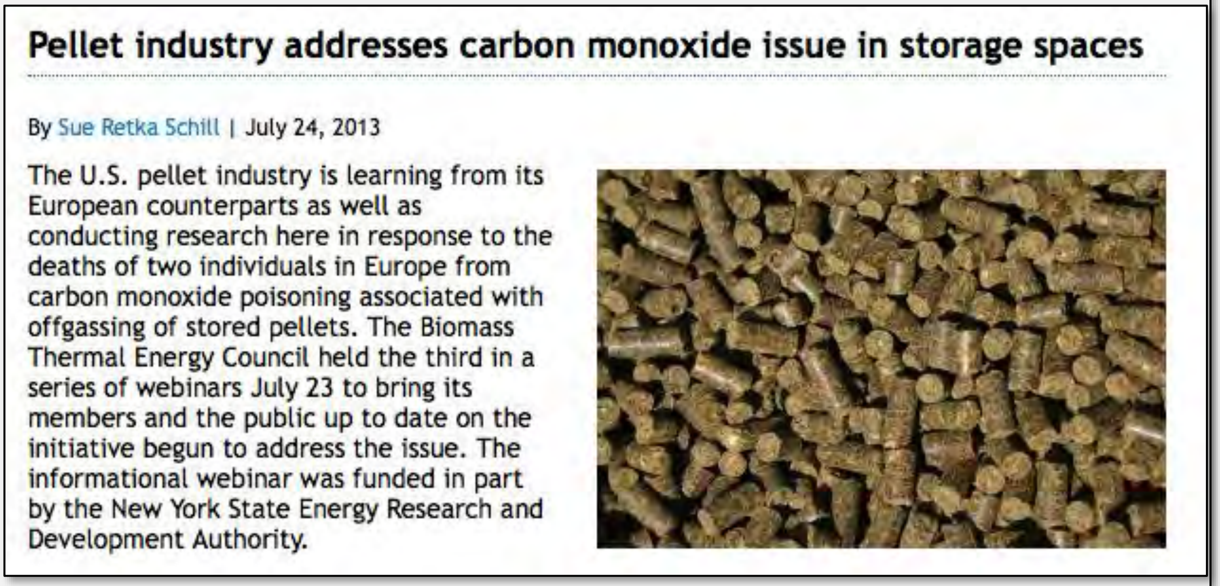


Fig. 2. Response of CO production by *Ascophyllum nodosum* incubated in darkness to various incubation temperatures. Open symbols represent fresh, living samples; closed symbols represent desiccated, non-living samples. All data are means of triplicate assays ± 1 SE

Appendix B. Non-Combustion CO Release from Wood Pellets



Pellet industry addresses carbon monoxide issue in storage spaces

By Sue Retka Schill | July 24, 2013

The U.S. pellet industry is learning from its European counterparts as well as conducting research here in response to the deaths of two individuals in Europe from carbon monoxide poisoning associated with offgassing of stored pellets. The Biomass Thermal Energy Council held the third in a series of webinars July 23 to bring its members and the public up to date on the initiative begun to address the issue. The informational webinar was funded in part by the New York State Energy Research and Development Authority.

Biomass Magazine, 2016

Key Point: It was recently discovered that wood pellets used for biomass energy release significant quantities of CO without combustion.

Rahman and Hopke, 2016

- *Key Point: CO concentrations over 1000 ppm were generated from wood pellets without any combustion. "The analysis of collected gas samples during this period suggested that the temperature increase was caused aerobic microbial processes."*
- *"The reaction is initiated by the autoxidation of unsaturated compounds, including fatty acids and terpenes, by molecular oxygen."*
- *This research is relevant to Zone A because it identifies that degradation of fatty acids creates CO, and fatty acids are in high concentrations at Zone A due to biodegradation.*

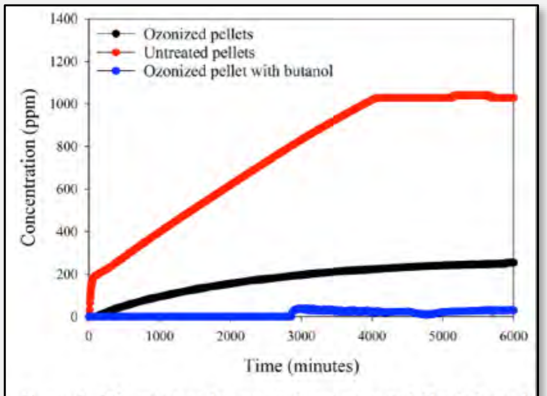


Figure 5. CO emissions by ozonized and unreacted blended wood pellets.

Appendix B. Non-Combustion Carbon Monoxide Generation at Landfills

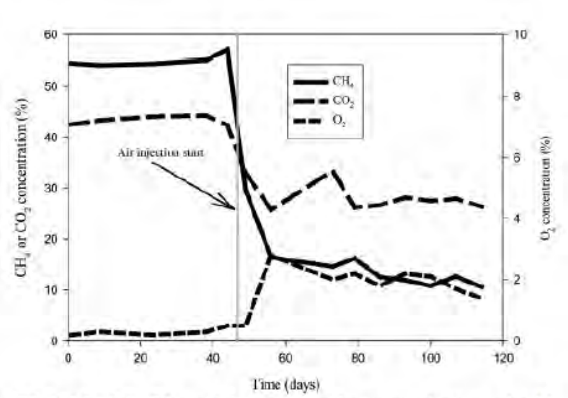


FIGURE 1. CH$_4$, CO$_2$, and O$_2$ concentration at monitoring point L2 before and after air injection.

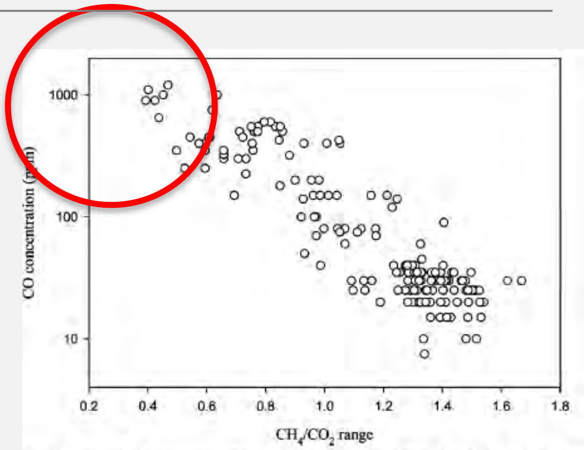


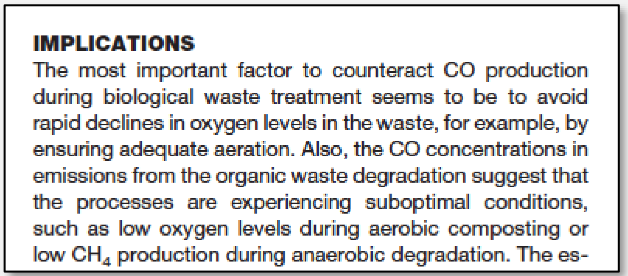
FIGURE 6. CO concentration as a function of the CH$_4$/CO$_2$ ratio at all monitoring points before and during air injection testing (n = 168 samples).

Powell, Jain, Kim, Townsend and Reinhart, 2006

Key Point: Adding air to a municipal landfill generated CO concentrations over 1000 ppm without combustion.

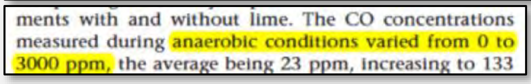
Haarstad, Bergesen, Sorheim, 2006

Key Point: Up to 3000 ppm CO was produced in lab experiments investigating solid waste degradation. Rapid reductions in oxygen levels increase CO production, as does low oxygen levels. (This research is relevant to Zone A because rapid reductions in oxygen level have occurred due to reductions in airflow over time).



IMPLICATIONS

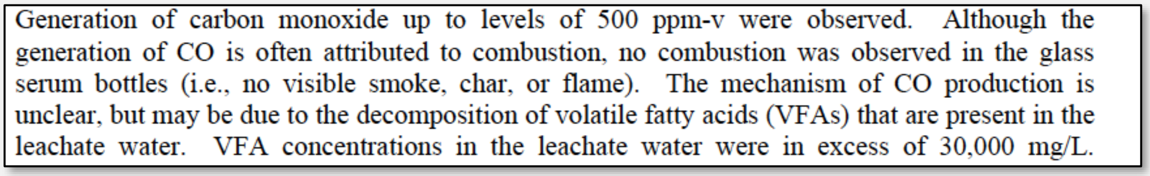
The most important factor to counteract CO production during biological waste treatment seems to be to avoid rapid declines in oxygen levels in the waste, for example, by ensuring adequate aeration. Also, the CO concentrations in emissions from the organic waste degradation suggest that the processes are experiencing suboptimal conditions, such as low oxygen levels during aerobic composting or low CH$_4$ production during anaerobic degradation. The es-



ments with and without lime. The CO concentrations measured during anaerobic conditions varied from 0 to 3000 ppm, the average being 23 ppm, increasing to 133

Walsh, 2007

Key Point: "It is a common misperception that CO is found in landfills only under conditions of active combustion or fire. The presence of CO in a landfill under non-combustion conditions has been well documented in the literature. These studies clearly indicate the chemistry that causes CO to be generated under conditions of elevated temperature. We conclude from this that CO may be an indication of landfill fire, but not exclusively so. Clearly, waste under somewhat elevated temperatures above 131 degrees also generates CO. Thus, if CO is to be used as an indicator of active landfill combustion, it should be used in combination with other monitoring data and physical observations, before any conclusion that combustion is occurring."

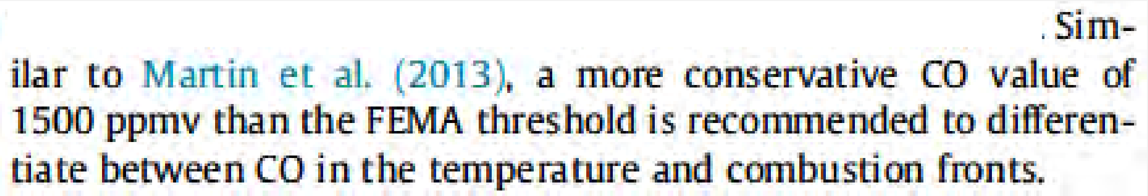


Generation of carbon monoxide up to levels of 500 ppm-v were observed. Although the generation of CO is often attributed to combustion, no combustion was observed in the glass serum bottles (i.e., no visible smoke, char, or flame). The mechanism of CO production is unclear, but may be due to the decomposition of volatile fatty acids (VFAs) that are present in the leachate water. VFA concentrations in the leachate water were in excess of 30,000 mg/L.

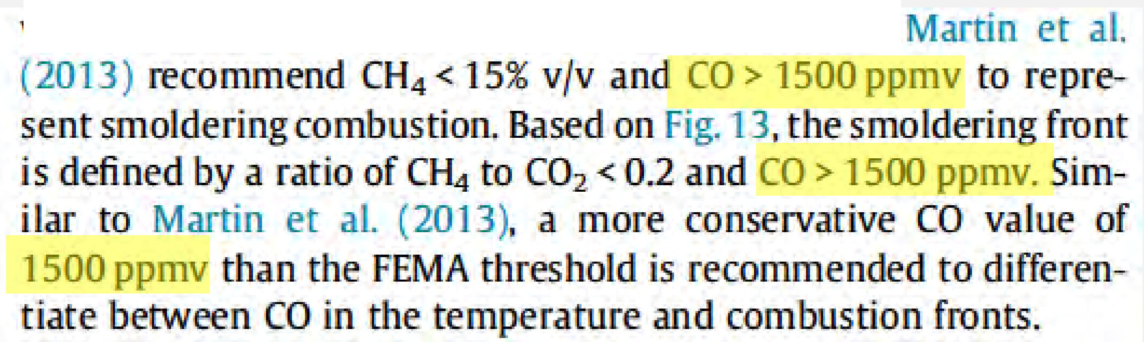
App. B. Criteria for Determining Combustion Front in Municipal Solid Waste Landfills

Jafari et al., 2017

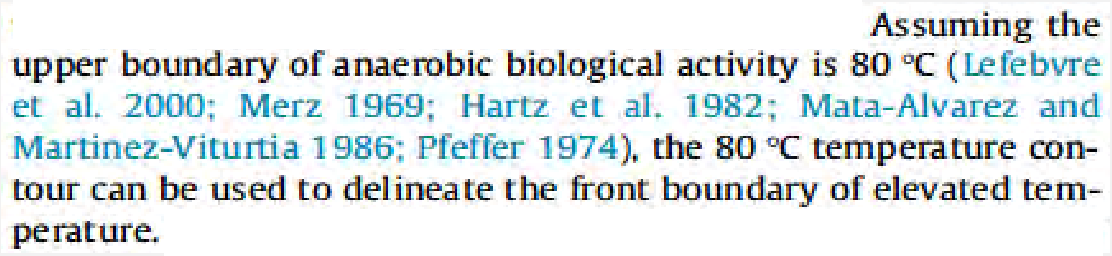
Key Point: Researchers are now relying on different criteria to detect areas of combustion than the 2002 FEMA guidance. Jafari et al. (2017) relies on a method developed by Martin et al., (2013) where a value of 1500 ppmv CO was used to define the actual combustion front.



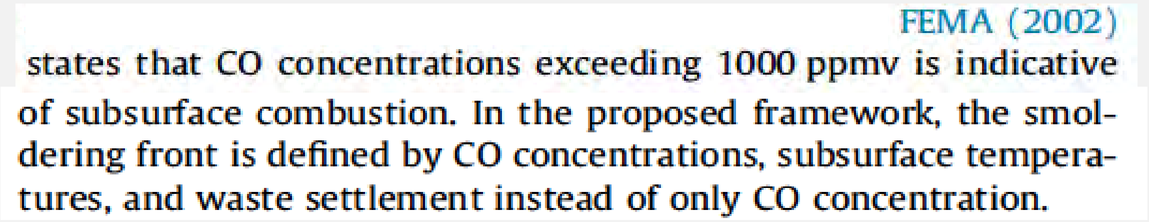
. Similar to Martin et al. (2013), a more conservative CO value of 1500 ppmv than the FEMA threshold is recommended to differentiate between CO in the temperature and combustion fronts.



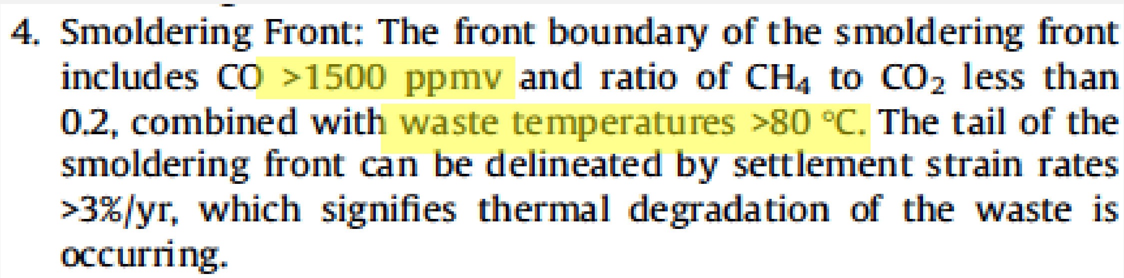
Martin et al. (2013) recommend $CH_4 < 15\%$ v/v and CO > 1500 ppmv to represent smoldering combustion. Based on Fig. 13, the smoldering front is defined by a ratio of CH_4 to $CO_2 < 0.2$ and CO > 1500 ppmv. Similar to Martin et al. (2013), a more conservative CO value of 1500 ppmv than the FEMA threshold is recommended to differentiate between CO in the temperature and combustion fronts.



Assuming the upper boundary of anaerobic biological activity is 80 °C (Lefebvre et al. 2000; Merz 1969; Hartz et al. 1982; Mata-Alvarez and Martinez-Viturtia 1986; Pfeffer 1974), the 80 °C temperature contour can be used to delineate the front boundary of elevated temperature.



FEMA (2002) states that CO concentrations exceeding 1000 ppmv is indicative of subsurface combustion. In the proposed framework, the smoldering front is defined by CO concentrations, subsurface temperatures, and waste settlement instead of only CO concentration.



4. Smoldering Front: The front boundary of the smoldering front includes CO >1500 ppmv and ratio of CH_4 to CO_2 less than 0.2, combined with waste temperatures >80 °C. The tail of the smoldering front can be delineated by settlement strain rates >3%/yr, which signifies thermal degradation of the waste is occurring.

APPENDIX C. AUTO-IGNITION TEMPERATURES

Constituent	Auto-ignition Temperature* (°F)
Acetone	869
Methyl ethyl ketone	760
Methyl isobutyl ketone	840
Toluene	995
Phenol	1319
Tetrachloroethene	NA (Non-combustible)
Trichloroethene	788
1,2-Dichloroethane	775
Isophorone	860
Gasoline	536
Paper	451
Wood	~600 to 900

* Auto-ignition temperatures based on an ~21% oxygen environment. Maximum downhole temperatures from 90° to 148°F.

NA = Not applicable.