Zone A Combustion Evaluation Report
Pasco Sanitary Landfill

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ABBREVIATIONS

BA	Bucket Auger Boring Location
CO	Carbon Monoxide
CO_2	Carbon Dioxide
ETL/ETLF	Elevated Temperature Landfill
FEMA	Federal Emergency Management Agency
GI	Gas Implant (Soil Gas) Probe Location
LEL	Lower explosive limit
MSW	Municipal Solid Waste
O_2	Oxygen
SVE	Soil Vapor Extraction
TC	Thermocouple Location
TVS	Total Volatile Solids

TITLE AND APPROVAL SHEET

ZONE A COMBUSTION EVALUATION REPORT
Pasco Sanitary Landfill

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EXECUTIVE SUMMARY

This Combustion Evaluation Report has been prepared on behalf of the Industrial Waste Area Generators Group III (IWAG) through the combined efforts of GSI Environmental, SCS Engineers, Environmental Partners, and Anchor QEA. The field program outlined in the *Revised Detailed Work Plan to Evaluate Potential Combustion in Zone A* is complete except as noted below. The objective of the field program described in the Work Plan was *"to gather sufficient data, through multiple lines of evidence, to allow for a clear evaluation of whether or not combustion is occurring beneath Zone A"* and *"allow(s) for monitoring of conditions in the future to assess changes in the subsurface of Zone A in response to modifications in ongoing SVE system operation."* Collectively, the six lines of evidence demonstrate that combustion is not occurring in Zone A and is not expected to occur in the future. Table E-1 summarizes the results and evidence for or against on-going combustion in Zone A. Table E-2 provides a summary of the combustion lines of evidence data generated by the testing program by monitoring location.

These data support the following conceptual site model:

- Extensive biodegradation, both aerobic and anaerobic, of the organic chemicals and to a lesser extent the mixed debris in Zone A are generating heat, carbon dioxide (CO_2), and carbon monoxide (CO) and are depleting oxygen (O_2).
- Carbon monoxide can be generated by biological processes and is not considered a reliable method to detect subsurface combustion when used as a single indicator.
- "Mixed debris," comprised of wood, cardboard, and other components of municipal solid waste (MSW) is found in Zone A in lenses separated by layers of interleaved silty sands and/or sandy silts with little to no organic content. Mixed debris was not detected in five of the 18 instrument borings and was a small fraction of material retrieved in the six large-scale bucket auger borings.
- The non-continuous nature of the mixed debris will prevent uncontrolled subsurface combustion that otherwise could occur in municipal landfills. The mixed debris in Zone A has little volatile material, and is a smaller contributor to the overall biodegradation processes at the site than the organic chemicals.
- Biodegradation reactions will result in a different signal than that resulting from either smoldering combustion or flaming combustion of mixed debris: 1) temperatures will be much lower because biodegradation can produce temperatures up to 176 °F while the first stages of spontaneous combustion in MSW requires at least 392 °F; 2) if oxygen concentrations are reduced over time, biodegradation can increase carbon monoxide while combustion shows the opposite signal; and 3) there will be only minor subsidence over time, not the several percent per year as shown by combustion in some MSW landfills.
- Multiple lines of evidence show that combustion is not occurring in Zone A. These lines of evidence were developed based on an extensive, multi-location, multi-depth, and multi-parameter monitoring program with over 30,000 temperature measurements; 100 soil gas measurements for six different gas parameters, over 200 vertical feet of large-scale bucket auger borings, and 18 smaller rotosonic borings distributed throughout the site. The average spacing between the edges of the two main cross sections (A-A' and C-C', see Figure 3.1) were both less than 45 feet, the detailed understanding of subsurface conditions generated from this Zone A monitoring program.
- Overall Zone A is much more like a large industrial Soil Vapor Extraction (SVE) remediation site, where combustion is typically not a concern, than a MSW site where subsurface combustion is not uncommon.

***Table E-1**. Combustion metrics, results, and analysis.*

OBSERVATIONS	CONCLUSIONS
1. Visual Observation of Smoke	
Smoke and embers have not been observed in Zone A.	A positive detection of smoke is the most definitive indicator of combustion. **Evidence: Does not support combustion.**
2. In Situ Soil Temperatures	**Weighting: HIGH**
Maximum in-situ temperatures recorded were 159°F during the main testing period.	In-situ temperatures are within range of heat-generating biological processes (up to 176°F, Jafari et al., 2017a) and far below the range expected for initiation of spontaneous combustion (> ~392 °F) (Moqbel et al., 2010). **Evidence: Does not support combustion.**
3. Carbon Monoxide Concentration	
Highest lab CO observed from soil gas probes: 930 ppmv. Highest recent lab CO from routine monitoring of Intermediate Zone SVE extraction wells: 1400 ppmv. High 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**.**	CO concentrations > 1000 ppmv can be generated biologically, and recent 2016 landfill research states: *"…there are not sufficient data to provide guidance on indicator concentrations (for CO). Nonetheless, concluding that a landfill is 'on fire' based on elevated temperatures and elevated CO concentrations can be erroneous."* 2017 landfill research studies do not use the FEMA (2002) 1000 ppmv CO limit as the sole criteria to detect combustion, but use a higher value in combination with several other factors. **Evidence: Potential combustion cannot be not confirmed by this indicator alone.**
4. Carbon Dioxide/Oxygen Relationship	
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 municipal solid waste [MSW]-like material).	Most of the heat is coming from biodegradation of organic chemicals with relatively little being associated with mixed debris. Organic chemicals in soil are not susceptible to uncontrolled combustion; for example, subsurface combustion is not a concern in the vast majority of thermal remediation projects. **Evidence: Does not support combustion.**
5. Characteristics of Mixed Debris Layer	
The mixed debris was generally encountered in lenses separated or 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.	Fuel for subsurface combustion is required in the form of a continuous waste layer. Lack of contiguous mixed debris layers makes this site more like a conventional SVE remediation site and unlike a conventional MSW site. **Evidence: Does not support combustion.**
6. Total Volatile Solids (TVS) in Mixed Debris	
The average TVS value of the mixed debris in the large diameter borings is 11.4% and the average TVS value of all of 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 and it is not volatile; the portion that was initially volatile has largely decomposed and is no longer as combustible in any sense.	Low levels of combustible material in the Zone A mixed debris make combustion unlikely. **Evidence: Does not support combustion**
7. Gas Autoignition Temperature	
Test to be performed.	No results yet.

Table ES-1. *Summary of lines of evidence data for key locations in Zone A from main testing period. Soil gas data are average from Events 3 and 4 (see Section 6 for details). See Figure 3.1 for cross section locations.*

Cross-Section	Location	1. Visual Observation of Smoke	2. Maximum *In situ* Soil Temperature (°F)	3. Average Lab Carbon Monoxide Concentration ** (ppmv)	4. Average PID (ppmv)	4. Average Oxygen (%)	4. Material Being Oxidized Based on Carbon Dioxide/Oxygen Relationship	5. Characteristics/Thickness of Mixed Debris (MD) Layer. TC: Thermocouple Boring; GC: Gas Concentration Boring located ~ 5 feet away.			6. Total Volatile Solids (TVS) in Mixed Debris / Entire Boring	Combustion Indicated?
								TC Borings	Overlap	GC Borings		
C	TC/GI1-24	None	157	295	1,725	15	Combination	No mixed debris	0'	6.5' (3 layers)	BA-1 9.3% / 0.9%	No
C	TC/GI1-29	None	154	445	4,741	6	Combination					
C	TC/GI1-35	None	148	480	5,112	6	Combination					
C	TC/GI2-27	None	154	295	7,481	3	Chemicals	No mixed debris	0'	No mixed debris		No
C	TC/GI2-32	None	152	280	6,174	12	Chemicals					
C	TC/GI2-36	None	146	200	4,512	17	Chemicals					
C, B	TC/GI3-25	None	159*	280	4,558	1	Chemicals	2.5' (1 layer)	1'	3' (3 layers)	BA-3 14.1% / 1.6%	No
C, B	TC/GI3-30	None	157	205	4,504	16	Chemicals					
C, B	TC/GI3-37	None	147	295	3,756	13	Chemicals					
C	TC/GI5-21	None	143	295	3,479	7	Chemicals	5.5' (3 layers)	4.5'	9.5' (1 layer)		No
C	TC/GI5-28	None	150	305	4,474	1	Chemicals					
C	TC/GI5-33	None	151	280	4,585	1	Chemicals					
C	TC/GI6-25	None	150	160	3,357	0.4	Chemicals	4 (1 layer)	0'	3' (3 layers)	BA-6 13.9% / 0.9%	No
C	TC/GI6-29	None	153	765**	3,372	2	Chemicals					
C	TC/GI6-36	None	143	41	3,719	1	Chemicals					
B	TC/GI4-19	None	123	*<100 (meter)*	*1,063*	2	Mixed Debris	7.5' (1 layer)	1	3' (1 layer)	BA-5 6.6% / 0.9%	No
B	TC/GI4-24	None	125	*<100 (meter)*	*745*	1	Mixed Debris					
B	TC/GI4-30	None	124	*<100 (meter)*	*892*	0.4	Mixed Debris					
A	TC/GI7-23	None	123	*<100 (meter)*	*804*	15	Combination	1' (1 layer)	1'	3' (1 layer)	BA-2 19.2% / 0.3%	No
A	TC/GI7-26	None	129	120	1,507	15	Chemicals					
A	TC/GI7-29	None	132	320	2,997	13	Chemicals					
A	TC/GI7-33	None	135	285	2,266	14	Chemicals					
A, B	TC/GI8-26	None	139	78	1,427	19	Mixed Debris	No mixed debris	0'	No mixed debris	BA-4; 13.1% / 0.9%	No
A, B	TC/GI8-29	None	141	190	3,668	19	Mixed Debris					
A, B	TC/GI8-32	None	141	300	3,530	18	Chemicals					
A, B	TC/GI8-37	None	137	385	4,173	15	Chemicals					
A	TC/GI9-25	None	119	118	616	20	Mixed Debris	2.5' (2 layers)	0.5'	0.5' (1 layer)		No
A	TC/GI9-29	None	124	*<100 (meter)*	*641*	19	Mixed Debris					
A	TC/GI9-34	None	129	*<100 (meter)*	*797*	18	Mixed Debris					
A	TC/GI9-39	None	126	*<100 (meter)*	*879*	18	Mixed Debris					

* 160 °F measured during subsequent Six Day test ** 930 ppmv measured in Sample Event 1 at GI2-32.

In summary, 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, if implemented in a controlled, data-driven manner as discussed below.

Recommendations

Moving forward, the IWAG will complete the autoignition testing program for Zone A soil gas, as the last line of field evidence in this evaluation. It should be noted, however, that the composition and condition of the soil gas measured in Zone A do not suggest that autoignition of the gas is a concern at Zone A.

In addition, we recommend the following be applied as part of the on-going operation of the Zone A SVE system to monitor and assess critical parameters informing the conceptual site model.

- Continued monitoring temperature, particularly of the thermocouple locations that had small (≤ 5 ºF) increases in temperature during the testing program, with the recent re-programming of the dataloggers to measure temperature from Type T thermocouples from this point forward. Investigative work should be conducted to determine if the one inoperative thermocouple (TC2-16) can be brought back in service or otherwise be replaced if necessary.
- Track the shallow versus deep temperature thermocouple data to discern temperature fluctuations due to seasonal heating and significant barometric effects.
- Apply current landfill research that cautions against relying on single lines of evidence, particularly carbon monoxide alone, to assess subsurface combustion:
    - Barlaz et al. (2016) states "*[n]onetheless, concluding that a landfill is "on fire" based on elevated temperatures and elevated CO concentrations can be erroneous" and "Consequently, ETLFs often exhibit elevated temperatures and elevated CO concentrations, even though a landfill fire (combustion) is not present*."
    - Jafari et al. (2017a) advocated using these three criteria together for finding a "smoldering front": CO >1500 ppmv, and ratio of CH_4 to CO_2 less than 0.2; and in-situ waste temperatures >80 °C (176 °F). They concluded temperature was the most of these accurate metrics. Finally, they stressed that the "tail" of a smoldering front can be identified by high settlement rates (> 3% per year).
- Resume operation of the intermediate zone SVE wells after installation of the new RTO and upgraded monitoring and control system in a staged manner and carefully evaluate how soil gas concentrations and in-situ temperatures respond. Incorporate soil gas and vapor temperature data into the operational decisions for the SVE system to determine and calibrate the response of the Zone A system under different flowrate conditions.
- The consultant team has a high degree of confidence in our conclusions from the combustion study and believes data collection for implementation of the recommendations can be performed in the current periodic manner using discrete sample events. However, IWAG has advised they will evaluate and implement, if feasible, enhanced data collection methods with extraction from the intermediate wells to provide Ecology with additional assurances that operation of these wells would not result in combustion. One enhancement could be to implement continuous temperature monitoring of the in-situ soil thermocouples and vapor from the intermediate wells with the data used as control parameters by the SVE process control system so as to rapidly identify any significant changes in the subsurface.

The temperature monitoring data could be compared with other parameters relied upon in the recent landfill combustion literature to evaluate the conditions under which potential combustion could occur.

1.0 INTRODUCTION

1.1 Background

During initial testing of the upgraded soil vapor extraction (SVE) system at Zone A in the spring of 2012, elevated temperatures up to 123 degrees Fahrenheit (°F) were observed in the SVE effluent gas. The increase in vapor temperature was discussed with the Washington Department of Ecology (Ecology), which expressed concern that the rise in temperature was potentially indicative of subsurface combustion. From June to September 2012, the IWAG performed a comprehensive evaluation to assess whether or not the conditions in Zone A were indicative of either subsurface combustion or subsurface heating not associated with combustion (i.e., degradation of solid or industrial waste). These activities included:

- Temperature and chemical data collection;
- Evaluation of seven indicators of a heating event related to subsurface combustion in landfills; and
- Analysis of several geochemical indicators including oxygen (O_2)/carbon dioxide (CO_2) relationships; isotopic analysis; and other factors.

These activities were documented in the *Zone A Heating Evaluation*, Pasco Sanitary Landfill Site (Anchor QEA, 2012). The authors concluded: *"there is no evidence that the elevated subsurface temperature and elevated CO [carbon monoxide] 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."*

Since spring of 2012, the maximum wellhead vapor and maximum downhole temperatures have been 144 and 148 °F, respectively (Table 1.1).

Table 1.1. *Summary of key temperature datasets: Wellhead vapor temperatures and maximum borehole temperatures from the Zonge (2014) report. Highest value reported in red.*

	Maximum Wellhead Temperature March 2012 to Nov. 2016 (EPI, 2017) (°F)	**Wellhead Temperature / Maximum Borehole Temperature Log (Zonge, 2014)**		
		July 11, 2012 (°F)	**Feb. 11, 2013 (°F)**	**Jan. 16, 2014 (°F)**
VEW-6S	138	-	-	-
VEW-6I	144	-	-	-
VEW-6D	108	90 / 114	95 / 121	100 / 114
VEW-7S	125	-	-	-
VEW-7I	144	-	-	-
VEW-7D	110	90 / 120	89 / 116	98 / 111
VEW-04	-	90	75	71
VEW-05	-	128	121	115
VEW-51D	-	**148**	146	130
MW-52-S	-	117	131	135
MW-53-S	-	No data	133	133

In late 2016, carbon monoxide (CO) concentrations, up to 950 parts per million by volume (ppmv), in the SVE effluent gas at SVE well VEW-07I again raised concerns by Ecology and IWAG that subsurface combustion may be occurring (Table 1.2). To evaluate if combustion is occurring in Zone A or has recently occurred in Zone A, the *Revised Detailed Work Plan to Evaluate Potential Combustion in Zone A* (Work Plan) was developed and submitted to Ecology in November 2016.

The Work Plan was also designed to “allow for monitoring of conditions in the future to assess changes in the subsurface of Zone A in response to modifications in ongoing SVE system operation.” Ecology approved moving forward with the field program in December 2016 and field work was performed in December 2016 through April 2017.

Table 1.2. *Carbon monoxide concentrations January 2016 to March 13, 2017 (laboratory analysis). Highest value shown in red.*

	Carbon Monoxide (ppmv) Jan. 2016 to March 2017			
	Minimum	Median	Maximum	Most Recent
VEW-06S	<5	<5	<5	<5
VEW-06I*	37	355	1200*	1200*
VEW-06D	<5	5.4	8.6	8.6
VEW-07S	<5	5.5	12	12
VEW-07I*	520	730	**1400***	1100*
VEW-07D	8.8	20	25	20

** Values during period when regular well purging not performed*

1.2 Objective

The objective of the field program specified in the Work Plan was to gather sufficient data, through multiple lines of evidence, to allow for a clear evaluation of whether or not combustion is occurring beneath Zone A. Some of the results can also be used to evaluate the general likelihood of combustion in the future. This report presents the results from the field program. These results supplement and expand upon the previous heating evaluation and will provide a platform for monitoring of future conditions for assessing any changes in the subsurface of Zone A in response to modifications in the ongoing SVE system operation.

Key Points

- Elevated temperatures and carbon monoxide concentrations have raised concerns by Ecology and the IWAG that subsurface combustion may be occurring in Zone A.
- To address these concerns, a field program based on obtaining multiple lines of evidence was performed in early 2017 to allow for a definitive evaluation of whether or not combustion is occurring beneath Zone A.

2.0 LINES OF EVIDENCE TO EVALUATE POTENTIAL COMBUSTION

The following lines of evidence were presented in the *Revised Workplan to Evaluate Combustion in Zone A*. Several of these lines of evidence were taken from "Landfill Fires – Their Magnitude, Characteristics, and Mitigation" (FEMA, 2002), and supplemented by more recent information and other methods specific to Zone A. Table 2.1 summarizes the different data collected and the rationale behind each metric. These data were then used in a weighted line of evidence evaluation to evaluate combustion.

Table 2.1. *Lines of evidence to evaluate if combustion is occurring in Zone A.*

Metric	*Rationale*
1. Visual Observation of Smoke	*Smoke is a confirmatory indicator of subsurface combustion. (Note that steam is indicated instead of smoke if the ambient temperature is conducive for steam formation and the cloud dissipates quickly).*
2. *In situ* Soil Temperatures	*The FEMA landfill fire guidance from 2002 uses in situ soil temperature as an indicator of combustion. High-temperature bacteria grow within the range of 105 to 165°F, with an optimum growth rate between 130 to 150°F.*
3. CO Concentration	*The FEMA landfill fire guidance from 2002 uses CO as a general confirmatory indicator of combustion. CO is produced at landfills by non-combustion sources as well.*
4. Carbon Dioxide/ Oxygen Relationship	*A key question is the nature of the Mixed Debris Unit. Underground combustion of liquids and gases is not self-sustaining in soils, but solid continuous combustible material like carbonaceous landfill waste can support sustained combustion under the right conditions.*
5. Characteristics of Mixed Debris Layer	
6. Total Volatile Solids (TVS) in Mixed Debris	
7. Gas Autoignition Temperature	*The autoignition temperature of the gas mixture in the subsurface at Zone A is a valuable parameter to help gauge the overall risk of an autoignition event.*

2.1 Visual Observation of Smoke

Smoke is a confirmatory indicator of subsurface combustion. The FEMA 2002 guidance states that "[s]moke or smoldering odor emanating from the gas extraction system or landfill" is one of six factors that "generally confirms" underground combustion is occurring.

Note that if the ambient temperature is conducive for steam formation, then special care was taken to avoid false positive indicators of combustion. One key difference between actual smoke and steam being emitted from core material is that a steam cloud dissipates more quickly. Project results are presented in Section 4.

2.2 In Situ Soil Temperatures

The FEMA landfill fire guidance from 2002 states that "temperatures in excess of 170 °F" is one of six factors that "generally confirms" underground combustion is occurring. This is a reference to subsurface soil temperatures and not temperatures in the extraction system gas. Subsurface temperatures can be elevated by biodegradation (e.g., Warren and Bekins, 2015; ThermalNSZD.com, 2017). Experts in elevated temperature landfills state that *"the literature suggests that biological reactions may result in landfills at perhaps 160-170 °F*" (Barlaz et al., 2016a). Jafari et al. (2017a) cited several references to support their conclusion that the upper boundary of anaerobic biological activity is 80 °C (176 °F). Normal operating temperatures for municipal landfills are less than <131°F, but "high operating variances (HOVs) to allow temperatures above 131°F are not uncommon" (Barlaz et al., 2016a).

On the other extreme, Moqbel et al. (2010) performed research that showed: *"MSW was found to have an ignition initiation point near the lower end of waste components tested (200 °C)."* At this temperature (equivalent to 392 °F) a combustion scenario is very likely.

Project results are presented in Section 5.

2.3 CO Concentration

The FEMA landfill fire guidance from 2002 states that "elevated levels of CO in excess of 1,000 parts per million (ppm)" is one of six factors that "generally confirms" underground combustion is occurring. However, they warn that *"to confirm a subsurface fire using CO, the results must be acquired through quantitative laboratory analysis (using portable monitors may result in artificially high concentrations*)." The FEMA document noted*: "[i]n California, levels of CO in excess of 1,000 ppm are considered a positive indication of an active underground landfill fire."*

However, extensive research since the FEMA guidance was issued in 2002 has identified a number of non-combustion CO sources in the subsurface, and landfill experts now state: *"concluding that a landfill is "on fire" based on elevated temperatures and elevated CO concentrations can be erroneous"* (Barlaz et al., 2016b) (see text box to right).

Non-combustion processes that can produce CO include anaerobic production from mesophilic (25–40 °C or 77–104 °F) and thermophilic (up to 80 °C or 176 °F) microorganisms as well as pyrolytic reactions (Barlaz et al., 2016b).

Both FEMA (2001) and Barlaz et al. (2016) also caution that CO readings from meters can produce artificially high concentrations:

FEMA Landfill Fire Guidance

The FEMA landfill fire guidance from 2002 states that "elevated levels of CO in excess of 1,000 parts per million (ppm)" is one of six factors that "generally confirms" underground combustion is occurring. However, they warn that *"to confirm a subsurface fire using CO, the results must be acquired through quantitative laboratory analysis (using portable monitors may result in artificially high concentrations*)."

The other five factors listed in the FEMA guidance included: substantial settlement, smoke or smoldering odor, combustion residue inside wells and headers, increase in gas temperature above 140 degrees F, and temperatures in excess of 170 degrees F.

We believe that no single factor can confirm the presence of a landfill fire. In theory, all these symptoms exist with a landfill fire, even though some may not be observable. But a preponderance of data, or in this case a majority of these factors being seen, can only reasonably be used to confirm a landfill fire.

Moreover, CO readings in excess of 1,000 ppm may be associated with landfill fires, but are not exclusive to combustion occurring. A developing body of evidence confirms that CO can be found under non-combustion conditions. Extensive research since the FEMA guidance was issued in 200 has identified a number of non-combustion CO sources in the subsurface, and landfill experts now state: "concluding that a landfill is "on fire" based on elevated temperatures and elevated CO concentrations can be erroneous" (Barlaz et al., 2016b) (see text box to right). Thus, elevated CO readings alone cannot confirm a landfill fire, any more than any one of the other factors listed.

> *To confirm a subsurface fire using CO, the results must be acquired through quantitative laboratory analysis (using portable monitors may result in artificially high concentrations). (FEMA, 2002).*
>
> *Caution must be exercised when measuring CO levels in gas, especially when using hand-held meters simultaneously reporting CH_4, CO_2, O_2, CO, and balance gas (assumed to be N_2). The manufacturers of some meters have indicated that high levels of H_2 may be mistaken for CO. In addition, because H_2 is not measured directly by most hand-held meters, the user may assume that the elevated balance gas is only N_2 when it is actually $N_2 + H_2$. Given that CH_4 and CO_2 are normally the primary constituents in LFG, the presence of high H_2 concentrations is atypical. Thus, the accumulation of H_2, as is sometimes observed in ETLFs, indicates that typical landfill biological processes have been interrupted. Therefore if a field meter indicates high CO or balance gas, and there is a trend of increasing gas well temperatures, then consider having gas samples analyzed by an accredited laboratory to determine if CO and H_2 are present. Elevated H_2 would suggest an ETLF as opposed to a landfill fire or SOE (subsurface oxidation event). (Barlaz et al., 2016b).*

New Understanding of Landfill Combustion since the 2002 FEMA Guidance

In 2015, the Environmental Research and Education Foundation (2016) funded a research project titled: *"Understanding and Predicting Temperatures in Municipal Solid Waste Landfills."* The principal investigators of the project are Dr. Craig Benson of the University of Virginia, Dr. Morton Barlaz of North Carolina State University, Dr. Marco Castaldi of The City College of New York and Mr. Scott Luettich of Geosyntec Consultants.

In a recent article (Barlaz et al., 2016b), they summarized the current state of knowledge about elevated temperature landfills:

"A very small percentage of municipal solid waste (MSW) landfills in North America have reported elevated and increasing temperatures above those normally associated with a "hot gas well." Temperatures above 150°F or even 250°F have been reported in some cases. Some of these elevated temperature landfills (ETLFs), have received industrial wastes that may release heat, while others have not. Considerable uncertainty exists regarding why some landfills exhibit elevated and increasing temperatures."

"The activity of CO-producing microorganisms in landfills is not well understood. While they may have a role in producing CO when methanogens are inhibited, such as in (elevated temperate landfills) ETLFs, there are not sufficient data to provide guidance on indicator concentrations. ***Nonetheless, concluding that a landfill is "on fire" based on elevated temperatures and elevated CO concentrations can be erroneous."***

***"Consequently, ETLFs often exhibit elevated temperatures and elevated CO concentrations, even though a landfill fire (combustion) is not present.*"**
(Emphasis added.)

In a recent paper, Jafari et al. (2017) rejected use of the FEMA (2002) CO limit alone to identify combustion. They used four lines of evidence:

> *"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."*

Jafari et al. (2017a) used "*spatial and temporal characteristics of elevated temperatures"* in two elevated temperature municipal solid waste landfills and defined a classification system with the following criteria:

1. *Anaerobic Decomposition:* Gas temperatures below 65 °C (149 °F) and typical ratios of CH_4 to CO_2 greater than or close to unity.
2. *Gas Front:* Decreasing ratio of CH_4 to CO_2 and gas wellhead temperatures at or below the NSPS threshold of 55 °C (131 °F).
3. *Temperature Front:* Increasing gas wellhead temperatures and decreasing ratio of CH_4 to CO_2.
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 (176 °F). The tail

of the smoldering front can be delineated by settlement strain rates >3%/yr, which signifies thermal degradation of the waste is occurring.

In a second paper, Jafari et al., (2017b) reemphasize that CO can have a biological origin: *"Powell et al. (2006) monitored an aerobic landfill and detected average CO levels of 245 ppmv with a maximum concentration of 1,200 ppmv. Waste temperatures remained below 76°C during the study, so Powell et al. (2006) concluded that CO was produced as a result of biological degradation of the waste under limited oxygen conditions." (Note that 76°C is 168°F).*

In summary, there has been important new research in elevated temperature municipal landfills over the past two years. A research team representing the University of Virginia, North Carolina State University, The City College of New York, and Geosyntec Consultants have cautioned (Barlaz et al., 2016b): "*[n]onetheless, concluding that a landfill is "on fire" based on elevated temperatures and elevated CO concentrations can be erroneous."* A recent paper by researchers from Louisiana State University, the University of Illinois, and California EPA have developed a classification system where a "smoldering front" is identified by soil temperatures exceeding 176 °F and CO concentrations > 1500 ppmv (Jafari et al., 2017), and not CO alone. These important studies are directly applicable to this Zone A Combustion Evaluation, as further indicated below. Project results are presented in Section 6.

2.4 Carbon Dioxide/ Oxygen Relationship

A key question regarding the potential for combustion in Zone A is the nature of what has earlier been referred to as "Mixed Debris." It is important to know whether the heat, consumption of oxygen, and production of carbon dioxide is more likely originating from the oxidation (either biodegradation or combustion) of:

- The mixed debris, which is largely comprised of wood, cardboard, and lesser amounts of municipal solid waste components; or
- The volatile organic compounds, represented by aromatics and ketones.

Because underground combustion of liquids and gases is not self-sustaining in soils, but solid continuous combustible material like carbonaceous landfill waste can support sustained combustion under the right conditions, knowing the main source of the underground reactions can help determine if subsurface combustion is occurring or may occur:

- If most of the oxygen being consumed and carbon dioxide being generated is from the oxidation solid/semi-solid carbonaceous materials (wood, paper, municipal solid waste) then it is **more** likely that subsurface combustion is occurring in Zone A.
- If most of the oxygen being consumed and carbon dioxide being generated is from the oxidation volatile organic liquids then it is **less** likely that subsurface combustion is occurring in Zone A.

The ratio of CO_2 to O_2 can be compared to a stoichiometric relationship to determine if the chemicals that generated a particular CO_2 to O_2 mix originated from organic chemicals like toluene, acetone, or methane vs. longer chained compounds like paper, wood, and MSW. This is presented in Section 7.

2.4 Characteristics of "Mixed Debris" and Total Volatile Solids in the Mixed Debris

A key question regarding the potential for combustion in Zone A is the nature of what has earlier been referred to as the "Mixed Debris" and if the mixed debris is present in enough sufficiently large and contiguous zones that could possibly support and sustain subsurface combustion. The differences between municipal landfill waste and most industrial sites are illustrated below:

- In municipal landfills, the entire waste zone is a potential interconnected combustion source that can support combustion, and municipal landfill subsurface combustion is a major concern.
- At contaminated industrial sites, liquid contaminants are confined to the pore spaces of the porous soil media that will not support combustion except under special engineered circumstances (e.g., engineered smoldering such as Savron's STAR process).

Underground combustion of liquids and gases is not self-sustaining in subsurface soils (Terratherm et al., 2001; Savron, 2016), but solid continuous combustible material like carbonaceous landfill waste can support sustained combustion under the right conditions (FEMA, 2002). Therefore, understanding the nature and continuity of the mixed debris is important for gaging the risk of subsurface combustion.

Total volatile solids (TVS) testing can also be used to determine the potential for combustion of the mixed debris in Zone A. As this will help to determine the amount of organics present in the subsurface. This analysis is presented in Section 8.

2.6 Gas Autoignition Temperature

The autoignition temperature of the gas mixture in the subsurface at Zone A is a valuable parameter to help gauge the overall risk of an autoignition event. In an email from Ecology on Feb. 27, 2015, Ecology stated:

> *Ecology has concern over any activities that potentially could push excess heat (and/or a combustion front) farther into the interior of Zone A and closer to the drums.*
>
> *The Online Chemical Handbook states that "Carbon disulphide has an extremely low autoignition temperature (125°C or 257 degrees F). May ignite or even explode when heated…Ignition temperature dangerously low: 212F." Historical SVE analyses indicate that carbon disulfide has been frequently detected, albeit at relatively low concentrations, in the SVE airstream. Highest concentrations have been reported at extraction well VEW-07i. Vapor samples collected from VEW-07i as recently as October 2014 contained detectable concentrations of carbon disulfide.*
>
> *Use of a 300 degree F threshold potentially introduces temperatures beneath Zone A which could exceed the autoignition or standard ignition temperatures for carbon disulfide (or possibly other gaseous constituents).*
>
> *The IWAG should use its own discretion over establishing temperature threshold criteria for this proposed upcoming CO2 injection event based on its current understanding and updated CSM of Zone A subsurface conditions – including but not limited to the recent auger-boring investigation results. We simply wanted to provide this point of perspective over the IWAG's proposed temperature threshold value.*

As part of this Work Program, a gas sample from one of the zones with high volatile organic compound (VOC) concentrations (including carbon disulfide) and relatively high oxygen concentrations will be collected to determine the autoignition temperature of the resulting gas mixture.

Key Points

- Seven lines of evidence will be used to evaluate potential subsurface combustion in Zone A: smoke, in-situ soil temperatures, carbon monoxide, characteristics of the mixed debris, Total Volatile Solids analysis of the mixed debris, carbon dioxide/oxygen relationships and that of other gasses, and autoignition testing.

3.0 FIELD PROGRAM TO EVALUATE POTENTIAL COMBUSTION

The field program consisted of two separate field activities/installations (Figures 3.1). As initial step, nine temperature/gas (“T/G”) monitoring stations were installed into Zone A: five between the randomly placed drums and stacked drum areas; three in the randomly placed drum area; and one near VMW-51D outside of the eastern boundary of the stacked drum area.

The mixed debris unit was sampled using a large-diameter bucket auger at six locations adjacent to the temperature/gas monitoring stations (see Figure 3.1). Bucket auger borings were advanced at the three locations in the randomly placed drum area.

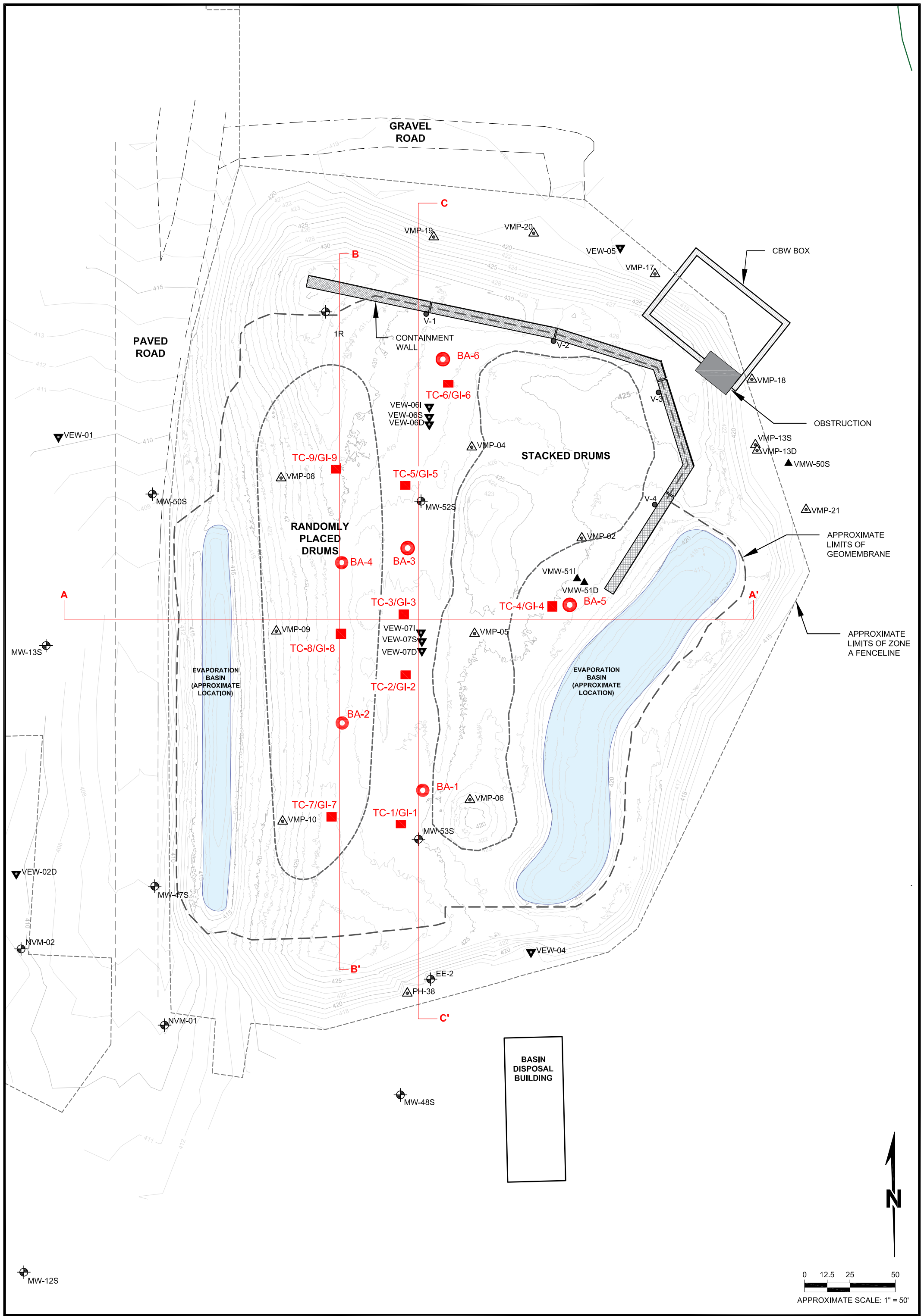
A conceptual cross section of the field program is shown in Figure 3.2. The detailed description of the field program is provided in Appendix A. Cross sections showing key results are shown in

- Figures 3.3a, b, c (Presence of Mixed Debris)
- Figures 3.4a, b, and c (Temperature)
- Figures 3.5a, b, and c (Soil gas)

Appendix B has a detailed description of the field program. Appendix D has an additional discussion regarding the temperature measurement program.

Key Points

- The field program specified in the Work Plan was implemented in early 2017 with only minor changes.



NOTES

EB-1	EXPLORATORY BORING LOCATION
MW-53S	MONITORING WELL LOCATION
VMP-17	VACUUM MONITORING PROBE LOCATION
TC-1/GI-1	THERMOCOUPLE AND GAS MONITORING LOCATIONS
BA-1	BUCKET-AUGER BORINGS

A A'
CROSS SECTION LOCATION

epi ENVIRONMENTAL PARTNERS INC

PROPOSED THERMOCOUPLE/GAS MONITORING
AND BUCKET-AUGER BORING LOCATIONS

PROJECT	03916.0		
PREPARED FOR	IWAG GROUP III PASCO LANDFILL		
LOCATION	1901 DIETRICH ROAD PASCO, WASHINGTON		
FIGURE 3.1	DRAWN BY VPB	REVIEWED BY ARM	DATE 4/19/17

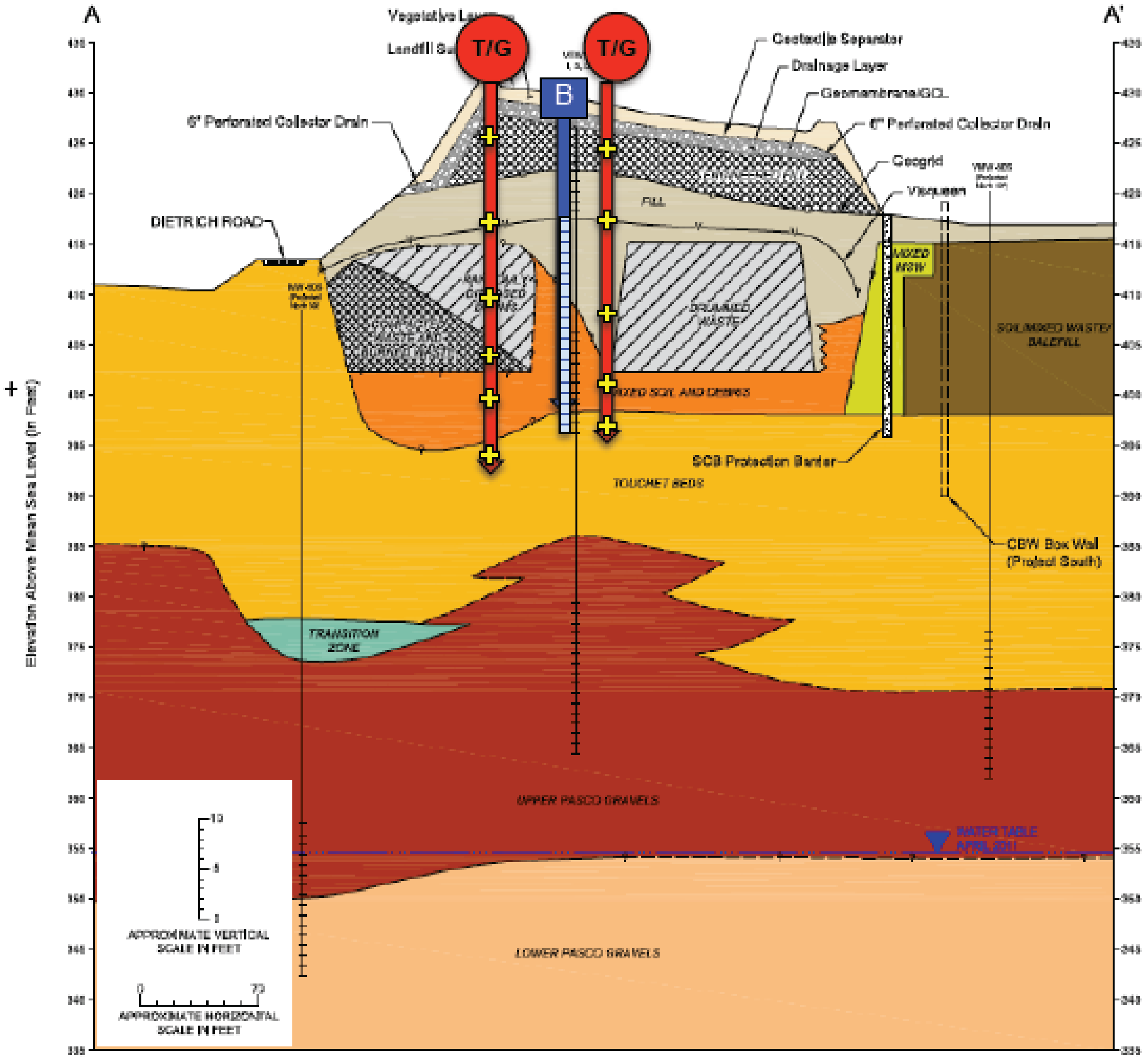
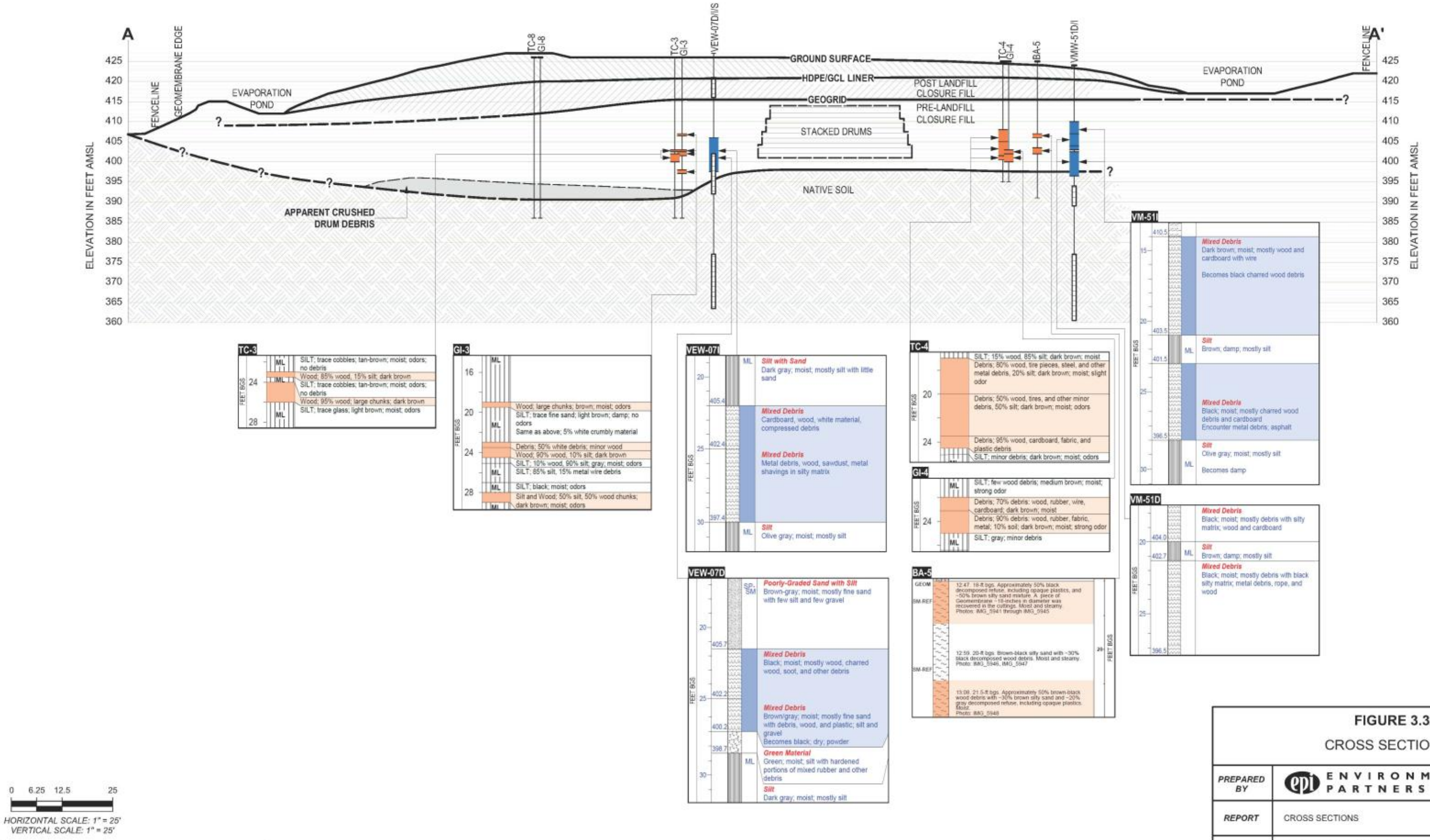


Figure 3.2. *Conceptual vertical placement of temperature/gas (T/G) monitoring points (yellow cross indicates where thermocouples and gas sampling tube screens are located) and the detailed bucket (B) auger target zone (hatched blue area shows where detailed coring/soil sampling will be performed below the visqueen layer). Source of original figure: SCS Engineers.*



HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 25'

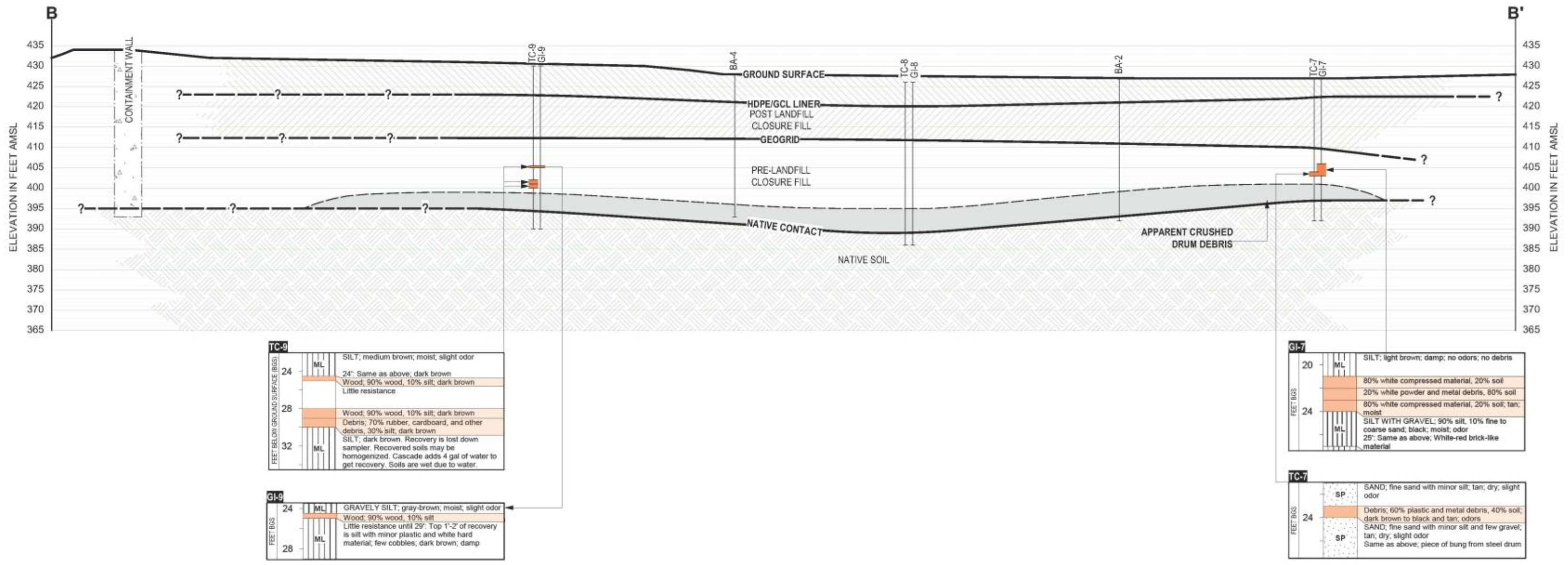
NOTES:

🟧	>50% NON-SOIL
🟦	PERCENTAGE OF NON-SOIL NOT ESTIMATED (2011 BORING LOGS)

FIGURE 3.3A

CROSS SECTION A-A'

PREPARED BY	ENVIRONMENTAL PARTNERS INC		
REPORT	CROSS SECTIONS		
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON		
PREPARED FOR	IWAG GROUP III		
DATE 4/24/17	***DRAWN BY*** VPB	***REVIEWED BY*** ARM	***PROJECT NUMBER*** 03916.0



0 6.25 12.5 25

HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 25'

NOTES:

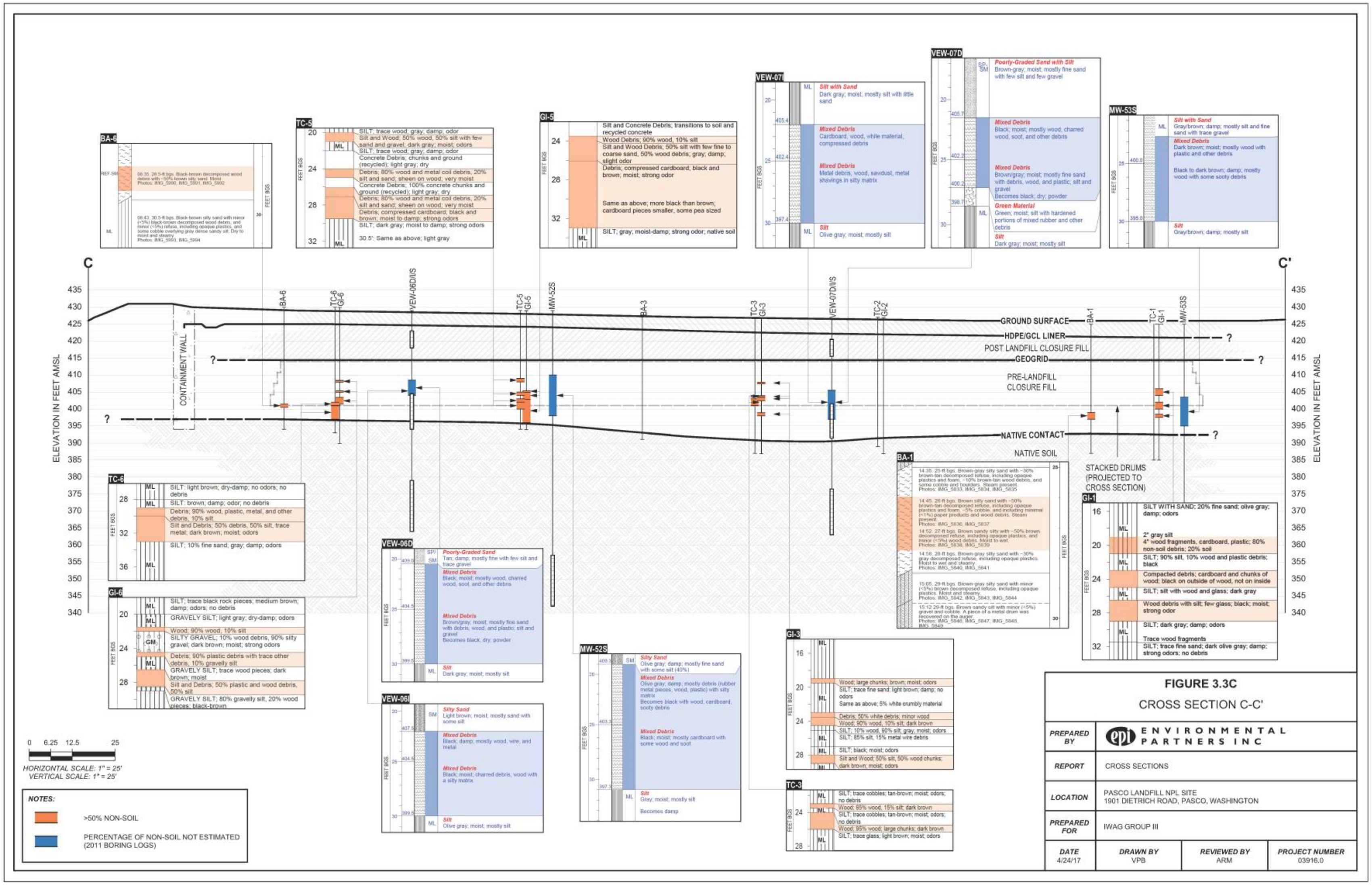
🟧 >50% NON-SOIL

FIGURE 3.3B

CROSS SECTION B-B'

PREPARED BY	ENVIRONMENTAL PARTNERS INC
REPORT	CROSS SECTIONS
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON
PREPARED FOR	IWAG GROUP III

DATE	***DRAWN BY***	***REVIEWED BY***	***PROJECT NUMBER***
4/24/17	VPB	ARM	03916.0



HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 25'

NOTES:

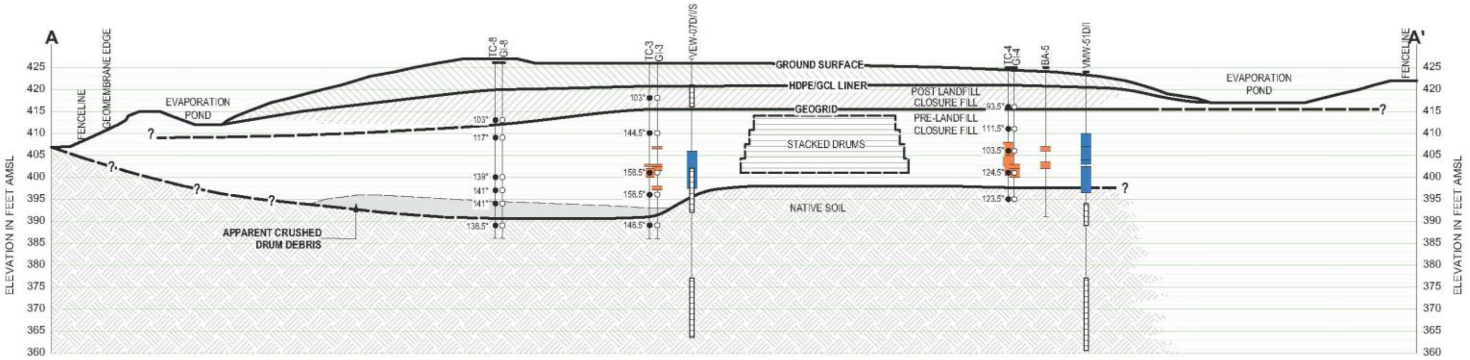
🟧	>50% NON-SOIL
🟦	PERCENTAGE OF NON-SOIL NOT ESTIMATED (2011 BORING LOGS)

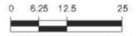
FIGURE 3.3C

CROSS SECTION C-C'

PREPARED BY	ENVIRONMENTAL PARTNERS INC
REPORT	CROSS SECTIONS
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON
PREPARED FOR	IWAG GROUP III

DATE	DRAWN BY	REVIEWED BY	PROJECT NUMBER
4/24/17	VPB	ARM	03916.0





HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 25'

NOTES:

🟧 >50% NON-SOIL

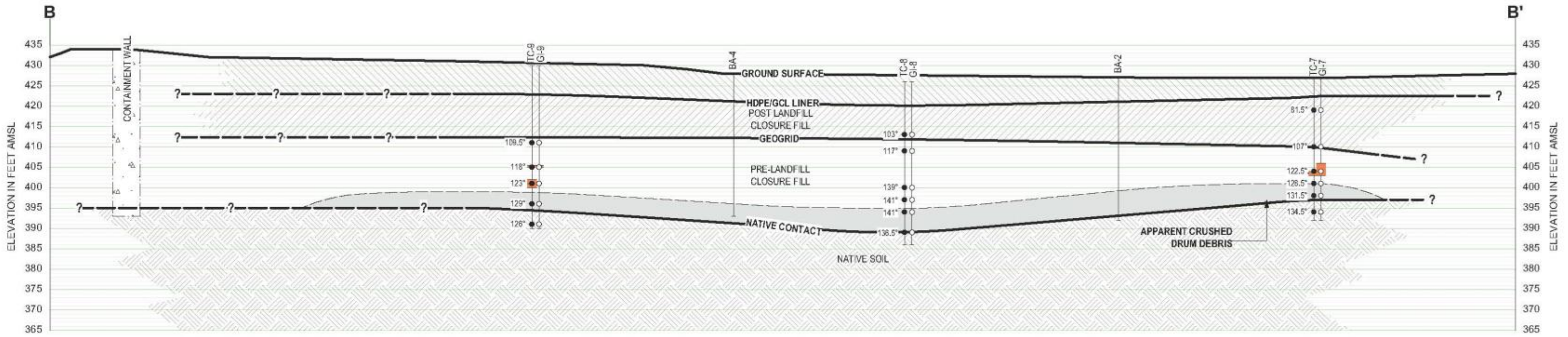
🟦 PERCENTAGE OF NON-SOIL NOT ESTIMATED (2011 BORING LOGS)

● THERMOCOUPLE LOCATION WITH MAXIMUM MEASURED TEMPERATURE (WEEK 4) IN DEGREES FAHRENHEIT

○ GAS IMPLANT LOCATION

FIGURE 3.4A
CROSS SECTION A-A'
TEMPERATURE MEASUREMENTS

PREPARED BY	ENVIRONMENTAL PARTNERS INC		
REPORT	CROSS SECTIONS		
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON		
PREPARED FOR	IWAG GROUP III		
DATE 4/24/17	***DRAWN BY*** VPB	***REVIEWED BY*** ARM	***PROJECT NUMBER*** 03916.0



0 6.25 12.5 25

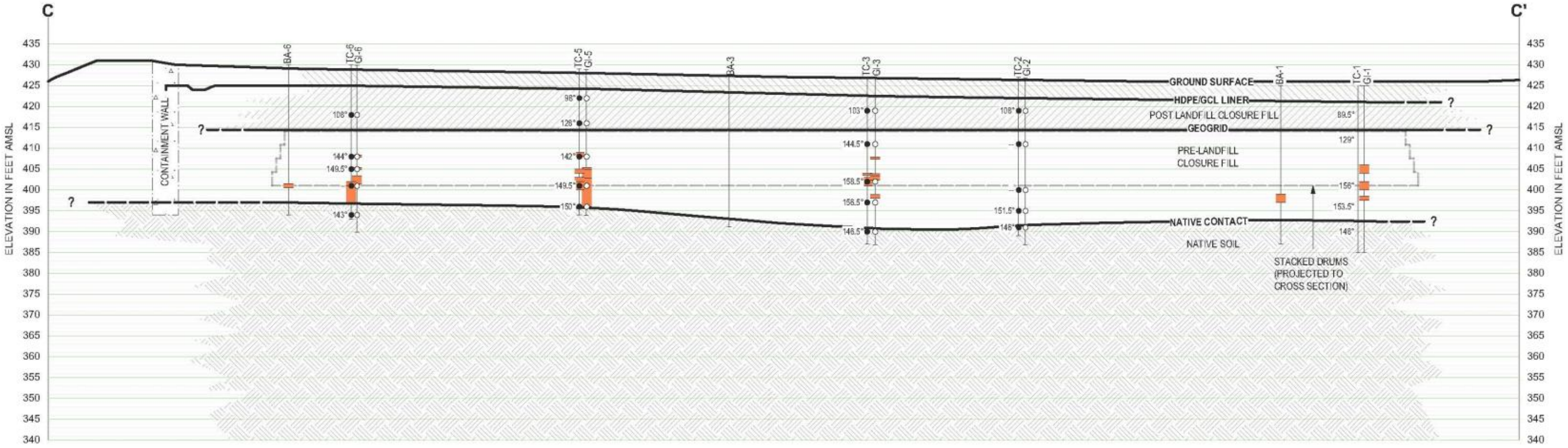
HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 25'

NOTES:

🟧	>50% NON-SOIL	●	THERMOCOUPLE LOCATION WITH MAXIMUM MEASURED TEMPERATURE (WEEK 4) IN DEGREES FAHRENHEIT
🟦	PERCENTAGE OF NON-SOIL NOT ESTIMATED (2011 BORING LOGS)	○	GAS IMPLANT LOCATION

FIGURE 3.4B
CROSS SECTION B-B' WITH
TEMPERATURE MEASUREMENTS

PREPARED BY	ENVIRONMENTAL PARTNERS INC		
REPORT	CROSS SECTIONS		
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON		
PREPARED FOR	IWAG GROUP III		
DATE 4/24/17	***DRAWN BY*** VPB	***REVIEWED BY*** ARM	***PROJECT NUMBER*** 03916.0



0 6.25 12.5 25

HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 25'

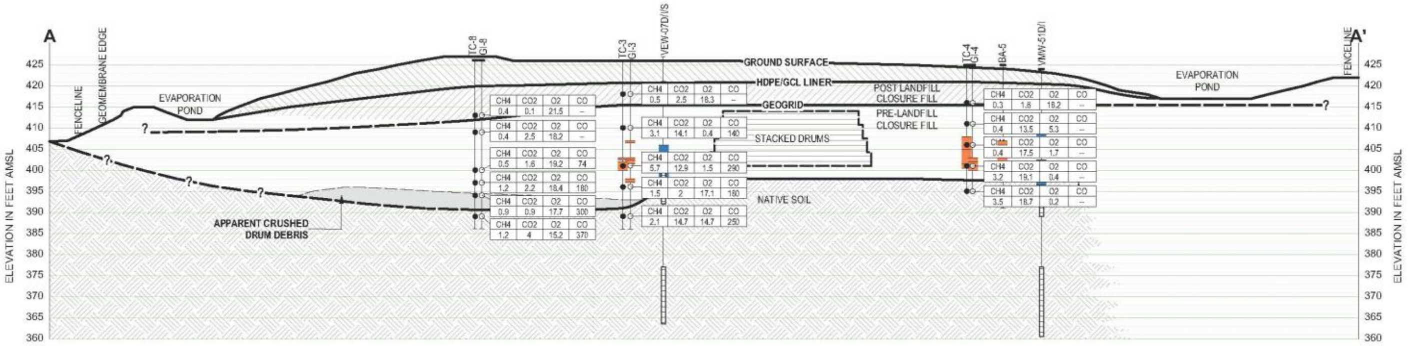
NOTES:

🟧	>50% NON-SOIL
🟦	PERCENTAGE OF NON-SOIL NOT ESTIMATED (2011 BORING LOGS)
●	THERMOCOUPLE LOCATION WITH MAXIMUM MEASURED TEMPERATURE (WEEK 4) IN DEGREES FAHRENHEIT
○	GAS IMPLANT LOCATION
--	THESE DATA ARE NOT RELIABLE DUE TO "K" EXTENSIONS

FIGURE 3.4C

CROSS SECTION C-C' WITH TEMPERATURE MEASUREMENTS

PREPARED BY	ENVIRONMENTAL PARTNERS INC		
REPORT	CROSS SECTIONS		
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON		
PREPARED FOR	IWAG GROUP III		
DATE 4/24/17	***DRAWN BY*** VPB	***REVIEWED BY*** ARM	***PROJECT NUMBER*** 03916.0



0 6.25 12.5 25

HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 25'

NOTES:

🟧 >50% NON-SOIL

🟦 PERCENTAGE OF NON-SOIL NOT ESTIMATED (2011 BORING LOGS)

● THERMOCOUPLE LOCATION

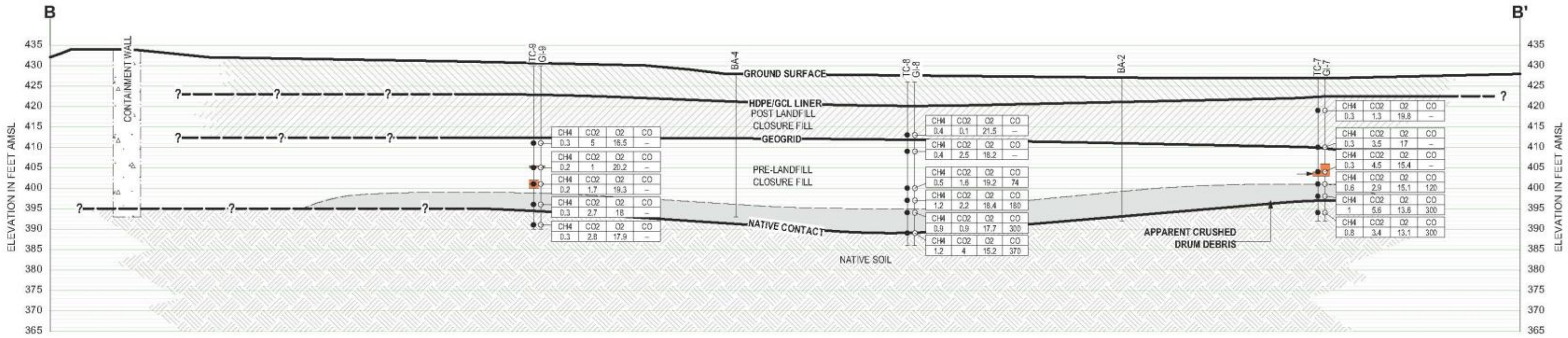
○ GAS IMPLANT LOCATION WITH GAS DATA COLLECTED DURING WEEK 4 FIELD ACTIVITIES

CH4	METHANE (PERCENTAGE)	MEASURED USING FIELD INSTRUMENTATION
CO2	CARBON DIOXIDE (PERCENTAGE)	
O2	OXYGEN (PERCENTAGE)	
CO	CARBON MONOXIDE (PARTS PER MILLION)	LABORATORY ANALYSIS

FIGURE 3.5A

CROSS SECTION A-A' WITH METHANE, CARBON DIOXIDE, OXYGEN, AND CARBON MONOXIDE MEASUREMENTS

PREPARED BY	ENVIRONMENTAL PARTNERS INC		
REPORT	CROSS SECTIONS		
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON		
PREPARED FOR	IWAG GROUP III		
DATE 4/24/17	***DRAWN BY*** VPB	***REVIEWED BY*** ARM	***PROJECT NUMBER*** 03916.0



CH4	CO2	O2	CO
0.3	5	16.5	–
0.2	1	20.2	–
0.2	1.7	19.3	–
0.3	2.7	18	–
0.3	2.8	17.9	–

CH4	CO2	O2	CO
0.4	0.1	21.5	–
0.4	2.5	18.2	–
0.5	1.6	19.2	74
1.2	2.2	18.4	180
0.9	0.9	17.7	300
1.2	4	15.2	370

CH4	CO2	O2	CO
0.3	1.3	19.8	–
0.3	3.5	17	–
0.3	4.5	15.4	–
0.6	2.9	15.1	120
1	5.6	13.6	300
0.8	3.4	13.1	300

0 6.25 12.5 25

HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 25'

NOTES:

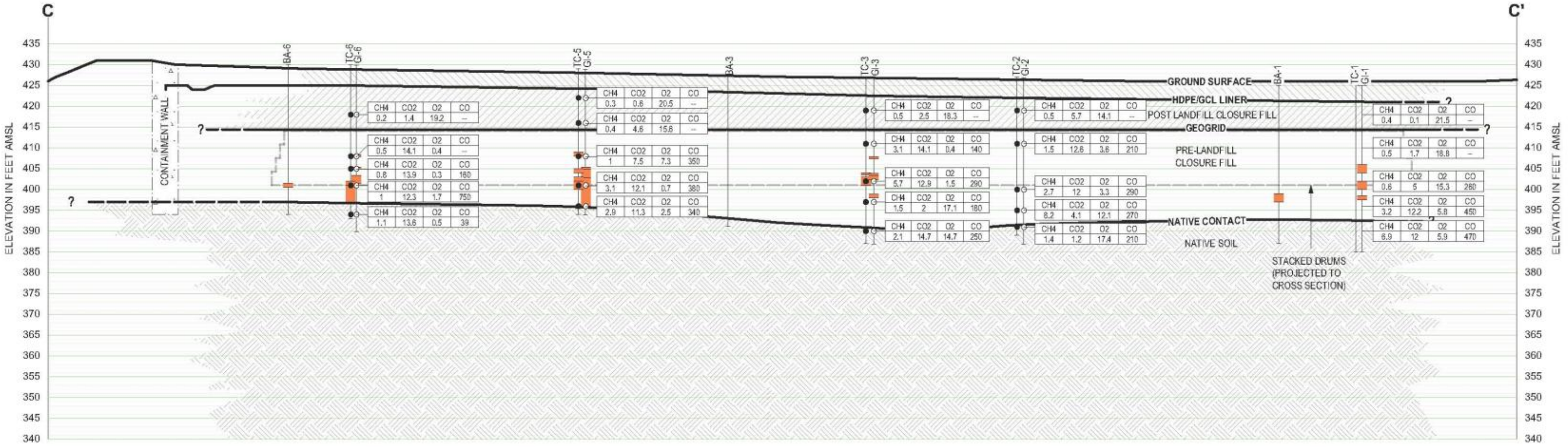
🟧	>50% NON-SOIL	●	THERMOCOUPLE LOCATION	CH4	METHANE (PERCENTAGE)
🟦	PERCENTAGE OF NON-SOIL NOT ESTIMATED (2011 BORING LOGS)	○	GAS IMPLANT LOCATION WITH GAS DATA COLLECTED DURING WEEK 4 FIELD ACTIVITIES	CO2	CARBON DIOXIDE (PERCENTAGE)
				O2	OXYGEN (PERCENTAGE)
				CO	CARBON MONOXIDE (PARTS PER MILLION)

CH4, CO2, O2: MEASURED USING FIELD INSTRUMENTATION
CO: LABORATORY ANALYSIS

FIGURE 3.5B
CROSS SECTION B-B' WITH METHANE, CARBON DIOXIDE, OXYGEN, AND CARBON MONOXIDE MEASUREMENTS

PREPARED BY	ENVIRONMENTAL PARTNERS INC
REPORT	CROSS SECTIONS
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON
PREPARED FOR	IWAG GROUP III

DATE	***DRAWN BY***	***REVIEWED BY***	***PROJECT NUMBER***
4/24/17	VPB	ARM	03916.0



0 6.25 12.5 25

HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 25'

NOTES:

🟧	>50% NON-SOIL	●	THERMOCOUPLE LOCATION	CH4	METHANE (PERCENTAGE)	MEASURED USING FIELD INSTRUMENTATION
🟦	PERCENTAGE OF NON-SOIL NOT ESTIMATED (2011 BORING LOGS)	○	GAS IMPLANT LOCATION WITH GAS DATA COLLECTED DURING WEEK 4 FIELD ACTIVITIES	CO2	CARBON DIOXIDE (PERCENTAGE)	
				O2	OXYGEN (PERCENTAGE)	
				CO	CARBON MONOXIDE (PARTS PER MILLION)	LABORATORY ANALYSIS

FIGURE 3.5C

CROSS SECTION C-C' WITH METHANE, CARBON DIOXIDE, OXYGEN, AND CARBON MONOXIDE MEASUREMENTS

PREPARED BY	ENVIRONMENTAL PARTNERS INC
REPORT	CROSS SECTIONS
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON
PREPARED FOR	IWAG GROUP III

DATE	***DRAWN BY***	***REVIEWED BY***	***PROJECT NUMBER***
4/24/17	VPB	ARM	03916.0

4.0 VISUAL OBSERVATION OF SMOKE

Smoke was not observed in any of the borings. Steam, however, was observed in all the borings beginning at depths as shallow as 8 feet below ground surface (bgs). Smoke tends to “hang” in the air since the ash, soot, and other small particles are suspended. Steam, on the other hand, will dissipate rapidly because it is water vapor that becomes part of the surrounding air. Temperatures within the large diameter borings were not observed in excess of 130 °F, based on the temperature of the material recovered from the boring. In addition to the relatively low temperatures observed, no burning material or embers were recovered from the borings. These materials would have been evident by the presence of flames, smoke, or glowing, even on a windy day. A summary of the subsurface conditions and a description of the materials encountered in the large diameter borings are described in boring logs presented in Appendix C.

Key Points Specific to the Visual Indication of Combustion

- During the drilling process smoke was not observed in any of the borings. Due to the relatively low ambient temperature as compared to the temperature of recovered materials, and the moisture content of the recovered materials, steam was present in each boring as shallow as 8 feet bgs. No signs of ongoing subsurface combustion were identified, including soil temperatures in excess of 170°F, flames, or embers.
- Dark and/or blackened recovered materials were observed in two of the six borings, BA-2 and BA-4. The recovered materials with darker color were primarily wood debris and soils mixtures with minor refuse content. However, it is not possible to determine if the darkened or blacked color is from combustion within the landfill during or immediately after initial disposal, if the color occurred prior to disposal, or from decomposition within the waste mass. It should be noted that Zone A area was operated as a burn trench prior to the early 1970s. The damp nature of the dark and blackened materials, lack of elevated temperatures and/or lack of smoke, flames, or embers indicates that the color is likely from decomposition or prior combustion.

5.0 IN SITU SOIL TEMPERATURES

5.1 Continuous Subsurface Temperature Measurements

For this project the key criteria for temperature measurements was the ability to discern actual combustion; i.e., temperatures of several hundred ºF; and determine if temperatures exceed two key benchmarks: 1) the expected upper level of biological activity (around 176 ºF, Jafari et al., 2017a) and 2) the lower temperature associated with potential combustion (> ~350 ºF, Moqbel et al., 2010). Thermocouples are commonly used instruments to measure temperature signals and have been applied at several sites to measure subsurface temperatures (e.g., ThermalNSZD.com; Jafari et al. 2017a, 2017b).

Continuous subsurface temperature measurements were collected during the period of January 25 through March 2, 2017 and then for six days in late March/early April. Type T thermocouples were installed at various depths at nine different locations throughout Zone A. Insulated with braided 304 or 316 SS for protection from corrosion, the thermocouples had a temperature measurement range of -454 to 700 ºF, with an accuracy of +/-1.0 ºC.

Temperatures were continuously recorded on an hourly basis using one datalogger per thermocouple (Lascar Electronics; model EL-USB-TC). Data loggers were housed in weatherproof protective enclosures throughout the duration of the investigation.

There were three factors that complicated the temperature data collecting and analysis:

- **Factor 1 – Datalogger Spikes:** When the data loggers were pulled from the enclosures for downloading, they would warm up to near room temperature. Because of the design of the dataloggers, short-term temperature spikes results (see Appendix D). For the data analysis in this report, the obvious spikes in the hours after reinstalling the data loggers were removed.
- **Factor 2 - Type K Extensions:** It is common practice to attach thermocouple wire extensions to extend the length of the original thermocouple wire that was purchased. For this project, incorrect extensions were used at several locations, resulting in invalid data for TC2-16, TC2-27, and TC6-29 locations (see Appendix D). The incorrect data are shown as faded lines in the figures below and in Appendix D but were not used in the temperature analysis. After the Main Test, two of the bad extensions were replaced, allowing temperature data to be collected from TC2-27 and TC2-29.
- **Factor 3 - Dataloggers Programmed to Read Type K Thermocouples.** Dataloggers from the 2014 Balefill study were reused for this study, but were not reprogrammed for the different thermocouple type (Type K for the Balefill study, Type T for this study). Data from the manufacturer and a short test (“Six Day”) test after the main test confirmed the error caused by the datalogger programming was very small.

For consistency, all of the temperature data in this section is presented as uncorrected data using the original Type K datalogger setting and likely overestimate actual temperatures slightly on average by 1 ºF. In summary, the following Table 5.1 describes the thermocouple data collection efforts, complicating factors, and resulting impact on data analysis.

Table 5.1. *Summary of Data Collection Efforts and Complicating Factors*

Data Collection Effort	Time Period	Complicating Factors and Correction Methods	Resulting Impact on Data Analysis
Main Test	Jan. 25 – Mar. 3, 2017	Complicating Factors: 1. Datalogger spikes 2. Type K extensions 3. Dataloggers programmed to read Type K thermocouples	Data from TC2-16, TC2-27, and TC6-29 were not used.
Six Day Test	Mar. 30 – April 2, 2017	All Type K extensions removed except for TC2-16 prior to Six Day Test Dataloggers reprogrammed to read Type T thermocouples in second-half of Six Day Test	Data for TC2-27, and TC6-29 from the first three days of the test were used in this report. Data from TC2-16 not shown. Test confirmed that: i) datalogger programming had small impact on results from Main Test, so no changes to data were made; and ii) Type K extensions used from Phase 2 of the Balefill Area project provided reliable data, so no changes were made.

5.2 Understanding the Seasonal Temperature Signal

To help explain the observed temperature record, a simple seasonal soil temperature model (Hillel, 1982) was applied to the Zone A dataset in order to understand naturally occurring subsurface temperatures at various depths over time:

$$T(z,t) = T_a + A_o e^{-z/d} \sin\left[\frac{2\pi(t-t_o)}{365} - \frac{z}{d} - \frac{\pi}{2}\right]$$

In this model,

- T **(**z, t**)** is the soil temperature at time t (days from the start of the year) and depth z(m),
- T_a is the average soil temperature (◦C),
- A_0 is the annual amplitude of the surface soil temperature (i.e., the difference between the maximum and minimum surface soil temperature, ◦C),
- d is the damping depth (m) of annual fluctuation, and
- t_0 is the time lag (days) from the start of the year to the occurrence of the minimum temperature in a year.
- A flat ground surface, uniform soils, and average seasonal weather conditions are assumed.

The damping depth is given by $d = (2D_h/w)^{0.5}$, where D_h is the thermal diffusivity of the soil and w, the frequency of the temperature variation, is $2\pi/365\ d^{-1}$.

As shown in Figure 5.1, the seasonal temperature changes will affect subsurface soil temperatures this way:

- For soils at 8-foot depth, temperatures fall in January through March, then increase through September. A temperature increase of over 25 ^{o}F may be observed.
- For soils at 12-foot depth, the temperature effect is smaller and lagged. An increase in temperature from April to late September of 25 ^{o}F may be observed.

- For soils at 25 and 30 ft depth, the seasonal temperature effect is much smaller, only a few degrees. Because of the time it takes the heat to get to these depths, the maximum soil temperature is expected in the winter, and the minimum occurs in the summer.

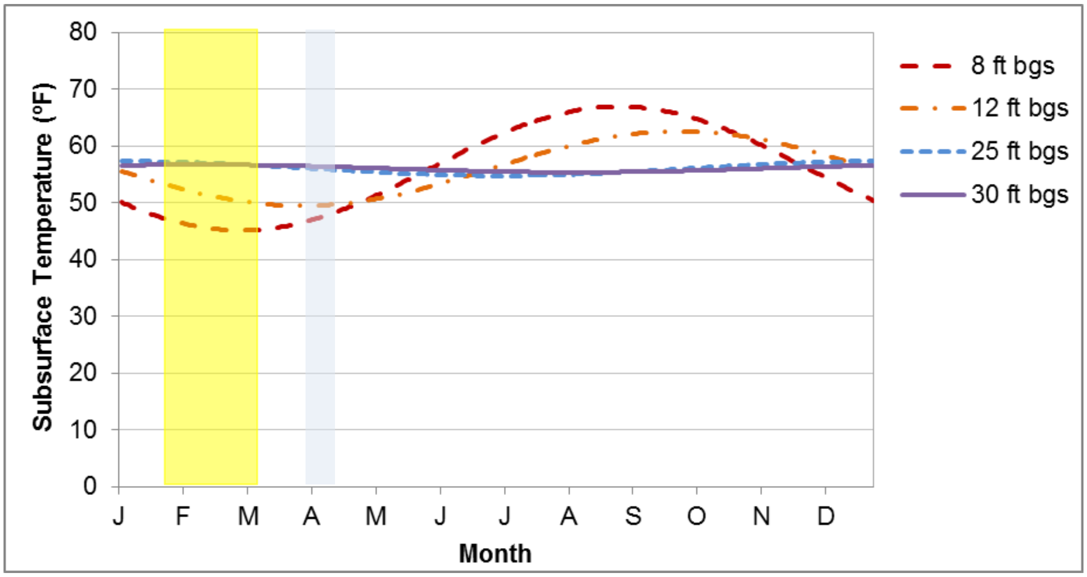


Figure 5.1. *The theoretical naturally occurring change in seasonal temperatures in the soils in Pasco Washington vs. depth. Yellow shows the time period for the primary data collection, January 25 to March 2, 2017 and blue the six-day text from March 30 to April 5, 2017. Shallow soil temperatures should fall in February and start to increase in late March / early April. Little seasonal change (just a few degrees) with a lag is expected in deep soil temperatures (25 and 30 ft bgs). Additionally, a time lag in the subsurface temperature signal exists with the deeper depths in which timing of high/low temperatures are shifted as compared to shallow depths.*

The soil temperature seasonal effects shown in Figure 5.1 were generated assuming generic, uniform soil conditions without any subsurface heating, surface cap, or other factors specific to Zone A. The magnitude and timing of the seasonal pattern will differ somewhat in Zone A.

5.3 Temperature Results

The maximum subsurface temperatures during the January 25 – March 2, 2017 time period at any location was 158.5 ºF, with 160 ºF observed in the subsequent six-day test in early April. The minimum temperature was 87.5 ºF (Table 5.2). Because the error was very small (average of +1ºF or +0.8% overestimate of the temperature; see Section 3.6 and Appendix B), the temperatures in this report were not adjusted to account for the datalogger being set for the incorrect thermocouple type (see Factor 3 above).

Figure 5.2 shows the temperature vs. time plot for the main test at the warmest location, TC-3 annotated with some explanatory notes. Temperature plots for all the locations are shown in Appendix D. The data for the three thermocouples with bad wire extensions are shown on the graph, but with faded lines to indicate these data are not reliable.

Table 5.2. *Summary of subsurface temperatures at each main test location. See Appendix D for results from the six-day test. Temperatures are uncorrected for data logger program setting; temperatures are on average 1 ºF too high.*

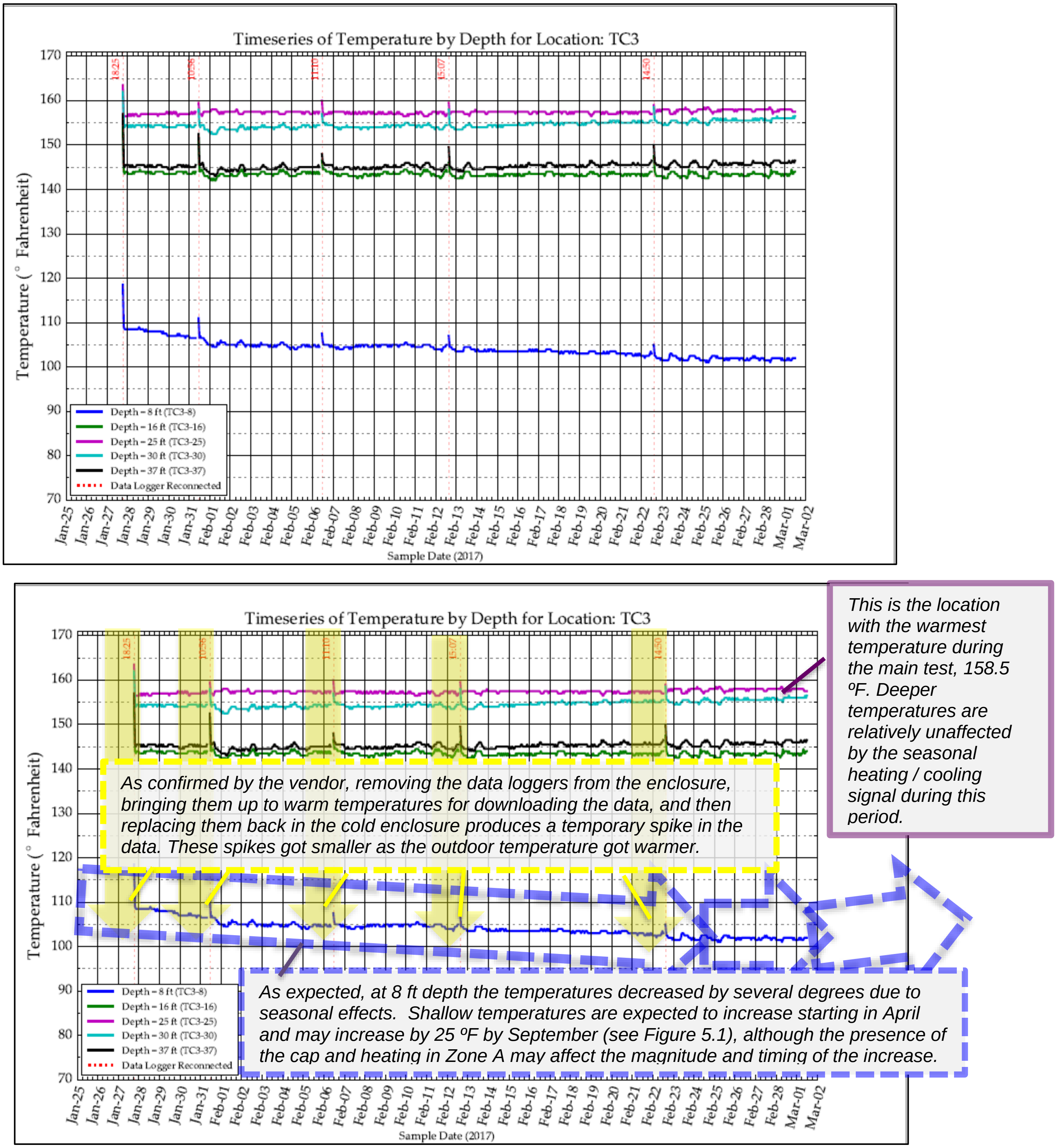
Location	Depth (ft bgs)	Temp. Minimum (ºF)	Temp. Maximum (ºF)	Average (ºF)
TC1	7	88	95	90
	14	128	131	130
	24	153	157	155
	29	151	154	153
	35	145	148	147
TC2	8	106	111	108
	16*	--	--	--
	27*	152	154	153
	32	148	152	150
	36	143	146	145
TC3	8	85	109	104
	16	142	145	143
	25	157	**159**	157
	30	153	157	155
	37	143	147	145
TC4	9	92	98	94
	14	110	113	111
	19	104	123	121
	24	122	125	124
	30	119	124	122
TC5	7	96	103	98
	12	127	131	129
	21	141	143	142
	28	147	150	149
	33	149	151	150
TC6	12	104	110	107
	22	140	144	142
	25	146	150	148
	29*	152	153	152
	36	141	143	142
TC7	8	77	88	82
	17	106	109	107
	23	120	123	122
	26	126	129	127
	29	118	132	130
	33	131	135	133
TC8	13	101	106	103
	17	116	119	117
	26	136	139	138
	29	138	141	140
	32	138	141	140
	37	134	137	136
TC9	19	108	110	109
	25	115	119	117
	29	122	124	123
	34	127	129	128
	39	124	126	125

:

1. (*) At TC2-16, data was invalid due to the different thermocouple extension type, and was excluded from figure (Factor 2). Data from the six-day validation test was used for TC2-27 and TC6-29 due to incorrect data during the Main Test (Factor 2).

2. (**) These thermocouples had Type K extensions from Phase 2 of the Balefill Area project, but exhibited no diurnal variations in the signal and subsequent analysis from the Six Day Test showed that this type of extension provided reliable data.

3. Results exclude temperatures from datalogger spikes in the hours after reinstalling dataloggers (see Factor 1).



This is the location with the warmest temperature during the main test, 158.5 ºF. Deeper temperatures are relatively unaffected by the seasonal heating / cooling signal during this period.

As confirmed by the vendor, removing the data loggers from the enclosure, bringing them up to warm temperatures for downloading the data, and then replacing them back in the cold enclosure produces a temporary spike in the data. These spikes got smaller as the outdoor temperature got warmer.

As expected, at 8 ft depth the temperatures decreased by several degrees due to seasonal effects. Shallow temperatures are expected to increase starting in April and may increase by 25 ºF by September (see Figure 5.1), although the presence of the cap and heating in Zone A may affect the magnitude and timing of the increase.

Figure 5.2. *Top: In-situ soil temperatures at location TC3. Bottom: Same graph but with annotations explaining some key points regarding the temperature data: spikes were created by datalogger downloading (yellow); seasonal temperature effects are seen in the shallow thermocouples (blue); and 3) the warmest temperature during the main test was 158.5 ºF (purple).*

Figures 5.3 and 5.4 show a side-by comparison of subsurface temperatures for all locations, with Figure 5.3 showing exact depths, and Figure 5.4 showing the depth interval. Key results are:

- The highest subsurface temperatures are at Location TC3 and the lowest are at TC4. Temperatures in cross section B'-B (random drum area) are lower than cross section C'-C (between the random drum and stacked drum areas).
- The expected declining seasonal soil temperature signal is seen in the data for the shallowest thermocouples (blue and black lines on Figures 5.3 and 5.4, respectively). The deepest thermocouples do not show a strong seasonal signal.
- TC4-19 thermocouple signal (purple line) was lost near the end of the record.
- A slowly increasing temperature trend is observed at several locations over the 33-day period, such as TC-3, TC-6 and TC-7. These data are discussed in more detail below.

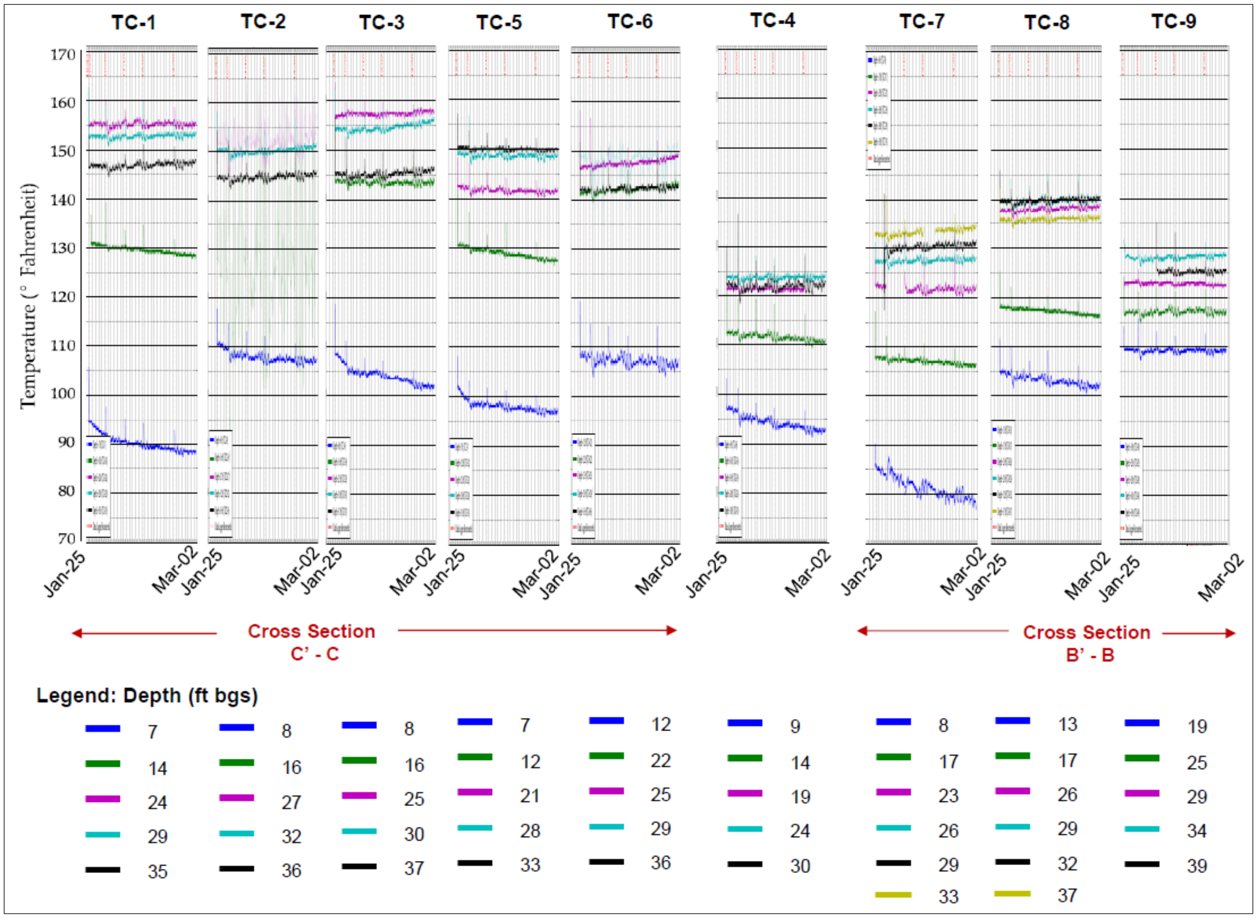


Figure 5.3. *Comparison of subsurface temperatures at all locations with unique depths per location. Data from TC2-16, TC2-27, and TC6-29 are shown as faded lines, but those data are unreliable due to use of incorrect wire extensions (Factor 2 above).*

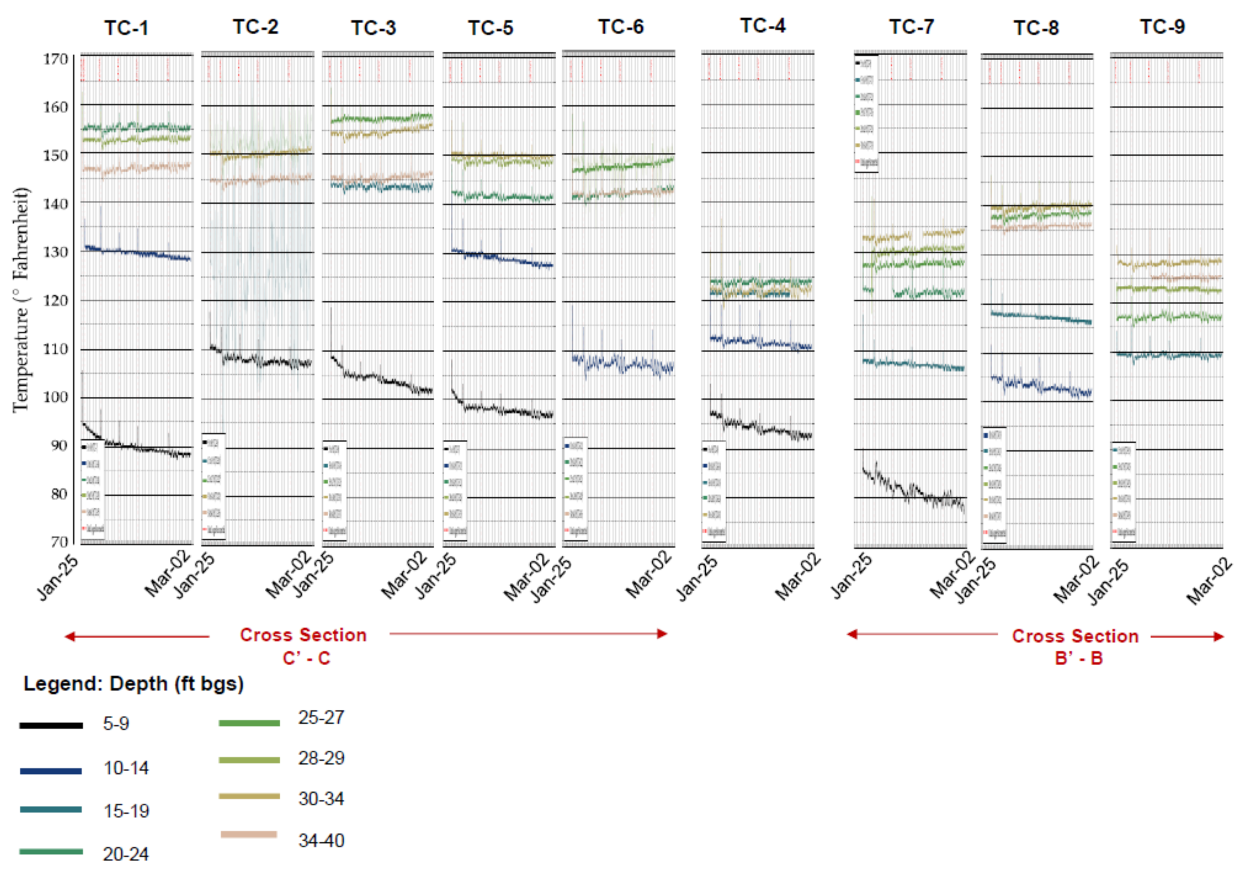


Figure 5.4. *Comparison of subsurface temperatures at all locations with similar depth ranges per location. Data from TC2-16, TC2-27, and TC6-29 are shown as faded lines, but those data are unreliable due to initial use of incorrect wire extensions (Factor 2).*

The temperature increase at TC6-25 increased slightly from about 147 to 149 ºF during the main test (Jan. 25 to March 2, 2017. At the end of the subsequent Six Day test, the temperature was 152 ºF on April 2, 2017. GSI's experience with evaluating background-corrected temperatures at SVE systems shows that 5 ºF changes in shallow soil temperature can occur by changing SVE operations over time, so this level of increases in Zone A may be associated with changes in the SVE extraction rate over the past year at the site combined with the slow travel time (months) for a heat signal to move through soils. For example, the flowrate in VEW-6D increased from about 173 SCFM to 202 SCFM on Feb. 21, 2017. An earlier increase in mid-2016 might also be contributing to this signal.

Note the oxygen measurements in the TC6-25 location were very low (0.2%) which is likely too low to support any type of combustion, even smoldering combustion, supporting the conclusion that combustion is not causing this small increase).

Another contributing factor may be the elevated configuration of Zone A which might produce different seasonal heating signals compared to the theoretical pattern shown in Figure 5.1. Overall, the absolute temperatures in the locations with increasing temperatures are all below the temperatures expected from actual smoldering combustion events, as shown in Figure 5.5 from the 2014 Balefill temperature monitoring program.

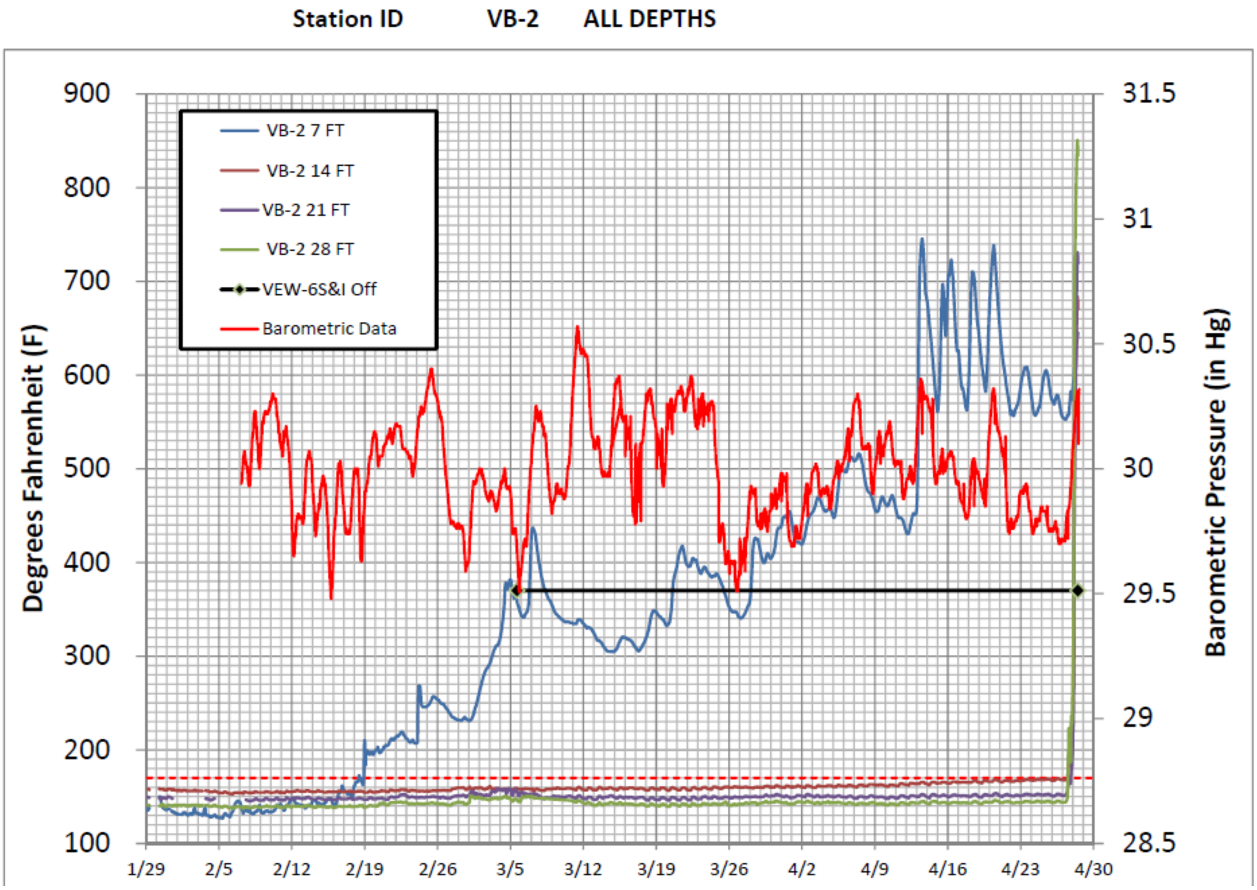


Figure 5.5. *Example temperature time series plot of subsurface combustion in Balefill Area in 2014.*

Figure 5.6 shows the average temperature profile over the Main Test vs. elevation; see also the temperature cross section Figures 3a, 3b, and 3c. At most of the locations, the highest temperatures are located in the 395 to 405 ft AMSL elevations, comprised of fill immediately above the native soil and corresponding to the likely zones with the highest organic contamination in soil and most likely heating zones. The thickness of the mixed debris did not seem to correlate to elevated subsurface temperatures; two locations with the most mixed debris (TC4 and TC5) had lower temperatures than adjacent thermocouple locations. Locations TC5 and TC6 had more mixed debris than TC3, but TC3 had the highest temperature. But as shown in Figure 5.6, none of the temperatures are in the range that indicates the potential for combustion.

Overall, the maximum temperatures seen in Zone A (158.5 ^{o}F during the Main Test and 160 ^{o}F during the Six-Day test) are not indicative of combustion in Zone A. (Note these are uncorrected temperatures; with the Type-T datalogger correction the maximum temperature was 157.5 ^{o}F during the Six Day test). FEMA recommends 170 ^{o}F as the threshold for in-situ soil temperature data. Jafari et al., (2017a) state that for determining different type of elevated temperature landfill conditions, *“Subsurface temperatures are the most accurate because they illustrate the dimensions and migration with time and can corroborate gas compositions”* and then recommends 80 ^{o}C (176 ^{o}F) plus carbon monoxide concentrations > 1500 ppmv to confirm the presence of a smoldering front. None of the locations observed in Zone A have reached either threshold.

Key Points Specific to Temperature

- Overall, the maximum temperatures seen in Zone A (159 ºF during the main test, 160 ºF during the six-day test) are within the range of temperature associated with biological activity (<176 ºF), are far below the lowest temperature associated with the onset of combustion (~392 ºF), and therefore are not indicative of combustion in Zone A.
- Temperatures do not appear to have any relationship to the presence of the thickness of the mixed debris layer.
- Soil temperatures decreased at all the shallow locations due to seasonal heating/cooling effects.
- Soil temperatures at a few deeper locations, for example, TC6-25 and TC7-33 increased by about 5 ºF from January to April, 2017. The highest temperature location, TC3-25, showed a 1.5 ºF increase between March 2 and April 5. This may be related to changes in the SVE system in Zone A. Non-seasonal fluctuations of this magnitude have been observed in other SVE systems where operations have changed over time, and do not suggest nearby combustion.

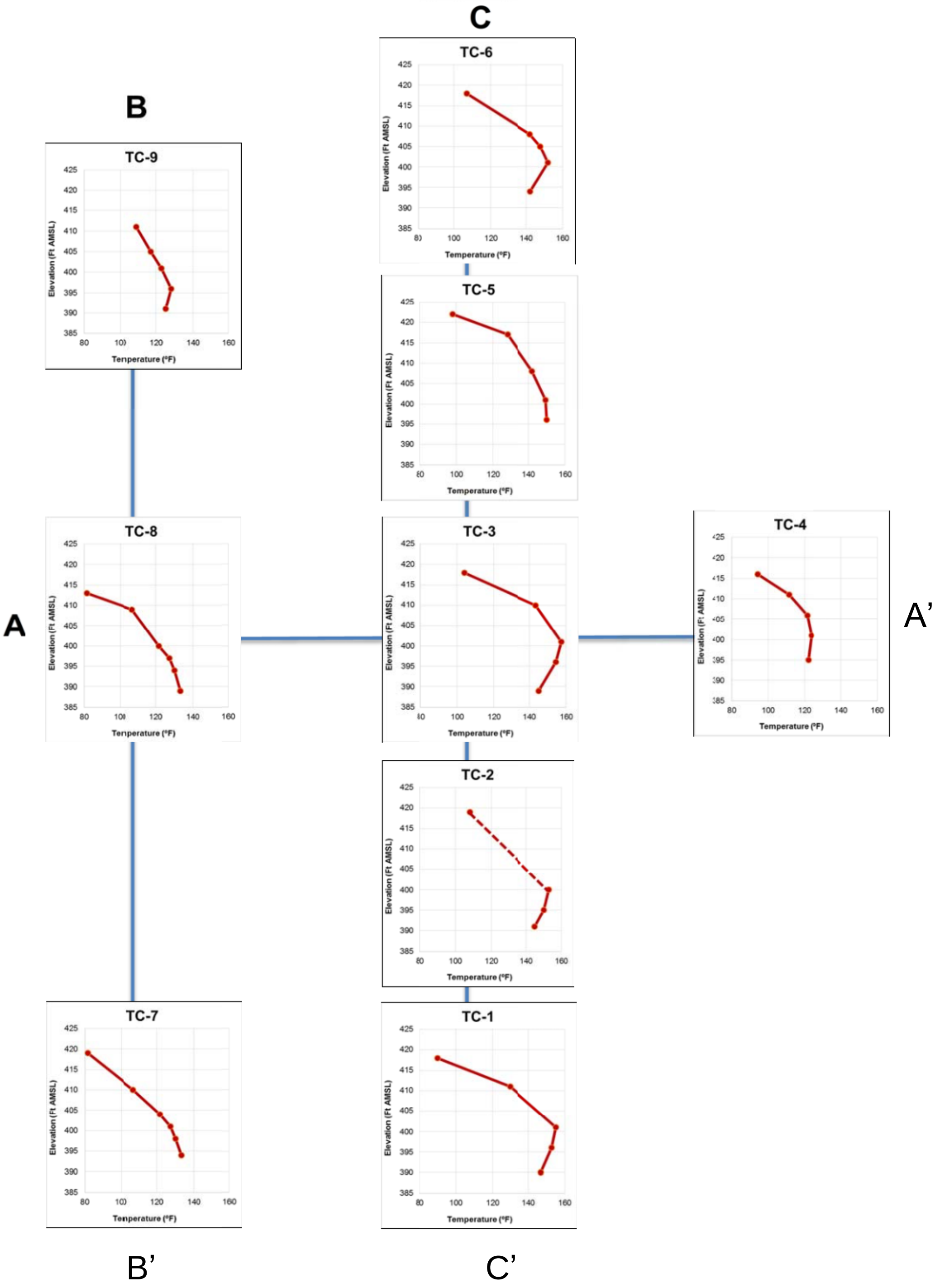


Figure 5.6. *Main test average temperature depth profiles arranged schematically along cross-sections in Zone A (see Figure 3.1)*

Notes: 1. Data from subsurface temperatures from February 28, 2017 (Week 4) depicted at all locations except TC-4, which includes February 22, 2017 (Week 3).

2. At TC-2, the thermocouple at 16 ft bgs depth had invalid data due to the different thermocouple extension type, and was excluded from figure. Data from the six-day validation test was used for TC2-27 and TC6-29.

6.0 CARBON MONOXIDE CONCENTRATIONS

6.1 Carbon Monoxide from Soil Gas Measurements

Measurements of carbon monoxide in soil gas were first conducted in the field using a meter. Laboratory samples were then collected and analyzed from these locations with a field meter reading greater than ~100 ppmv in order to focus the laboratory resources on only the high concentration samples. Results from the laboratory analysis program are shown in Table 6.1. All soil gas data in included as Appendix G.

As reported by field personnel, several sampling issues suggest that the first event (Feb. 7, 2017) and the second event (Feb. 14, 2017) may have data quality issues.

- *First Soil Gas Sampling Event:* Very cold weather conditions. Several of the soil gas connectors were frozen and condensate froze in some lines during sample collection. Eight of the 47 oxygen concentrations were significantly different (e.g., 0% vs. 15% oxygen) than the Week 3 and 4 sample events.
- *Second Soil Gas Sampling Event:* These samples collected at the same time that bucket auger drilling was being performed which may have affected some locations. As required by the health and safety plan, the SVE system was operating at this time which had the potential to draw atmospheric air into the subsurface through the open bucket auger borings. The bucket borings were proximal to several of the probe locations. Some unusual oxygen readings, both high and low, were observed. More importantly, ten lab CO readings were unexpectedly below detection limits.

Because of the above factors, most of the soil gas data analysis in this report relies on the third and fourth sample events, which experienced no field problems and no drilling related issues. However, because the high CO concentration was found during the first sampling event (Feb. 7, 2017), the data from three events (first, third and fourth) were included in data analysis that involved CO.

Locations GI4 and GI9 did not have any field measurements with CO > ~100 ppmv, therefore, no samples for laboratory analysis were collected.

The highest CO value from the combustion evaluation field program was 950 ppmv at location GI2-32 during the first sampling event. However, subsequent samples were much lower: 290 and 270 ppmv, respectively, for the third and fourth sampling events. To be conservative, however, the first sample event was retained in all CO analysis for this report. This is the same location where slightly increasing temperatures were observed (see Section 5.3).

Table 6.1. *Laboratory CO measurements for Feb. 7, 22, and 28, 2017. Samples were only collected from locations with field CO measurements > ~100 ppmv. Because of sample collection concerns, results from 2/14/17 are not shown.*

	First Event 2/7/17 Lab CO (ppmV)	Third Event 2/22/17 Lab CO (ppmV)	Fourth Event 2/28/17 Lab CO (ppmV)	Average of All Three Events (ppmv)
GI1-24	11	330	260	*200*
GI1-29	11	440	450	*300*
GI1-35	93	490	470	*351*
GI2-16	270	180	210	*220*
GI2-27	400	300	290	*330*
GI2-32	**930**	290	270	*497*
GI2-36	750	190	210	*383*
GI3-16	78	120	140	*113*
GI3-25	250	270	290	*270*
GI3-30	440	230	180	*283*
GI3-37	580	340	250	*390*
GI5-21	250	240	350	*280*
GI5-28	230	230	380	*280*
GI5-33	210	220	340	*257*
GI6-25	230	160	160	*183*
GI6-29	700	**780**	**750**	***743***
GI6-36	18	42	39	*33*
GI7-26	80	120	120	*107*
GI7-29	200	340	300	*280*
GI7-33	250	270	300	*273*
GI8-26	95	81	74	*83*
GI8-29	57	200	180	*146*
GI8-32	150	300	300	*250*
GI8-37	380	400	370	*383*

6.2 Relationship Between CO and Other Parameters

The relationship between laboratory CO and temperature is shown in Figure 6.1. The highest CO values did not correspond to the locations with the highest temperatures.

Figure 6.2 shows the relationship between CO and oxygen. The highest CO levels are in low oxygen zones, but below the 3% oxygen level which can support smoldering combustion (US Navy, 1998).

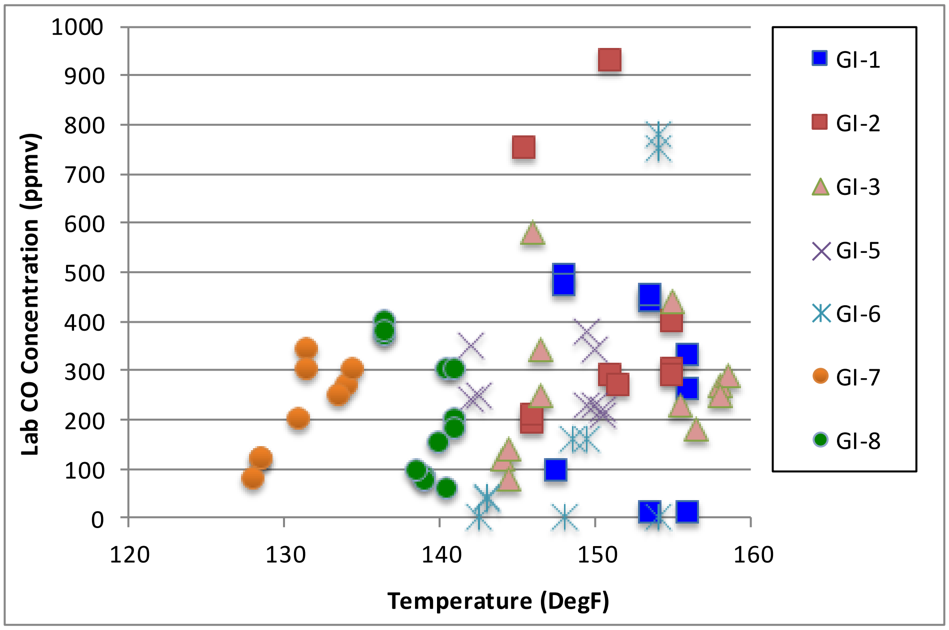


Figure 6.1. *Relationship between laboratory CO concentrations and temperature at locations with laboratory CO measurements (other locations did not have meter CO concentrations > 100 ppmv). Data is from the first, third, and fourth sampling events that had reliable CO data. Two locations used temperatures from the Six Day test because of extension issues. See Appendix G for soil gas data*.

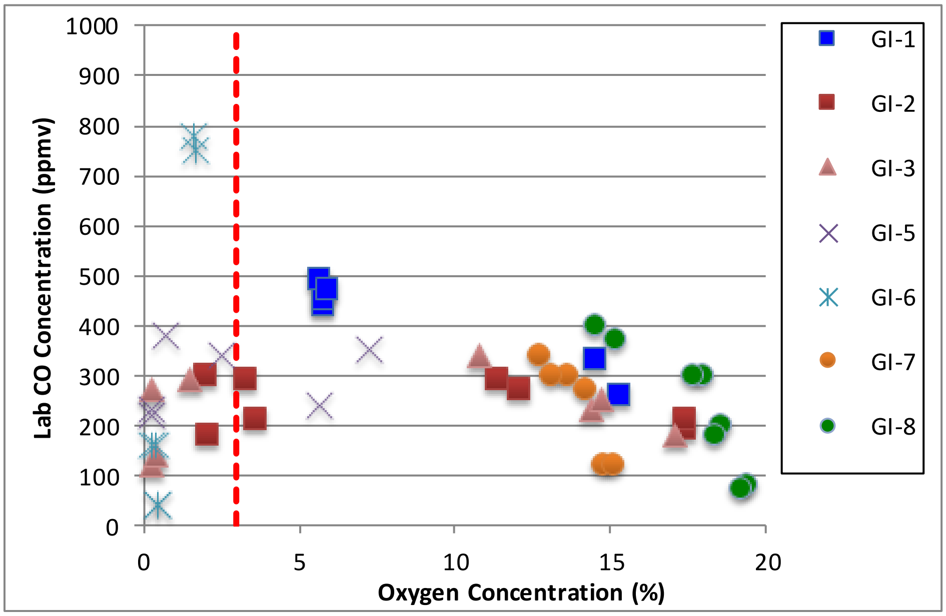


Figure 6.2. *Relationship between laboratory CO and oxygen concentration at locations with laboratory CO measurements (other locations did not have meter CO concentrations > 100 ppmv). Data is from the third and fourth sampling events that had reliable soil gas data (the first sampling event did not have reliable soil gas data and, therefore, the CO data from that event are not shown. The highest CO is located in low oxygen areas below the Minimum Oxygen Concentration (MOC) that can support smoldering combustion. See Appendix G for soil gas data*.

Figure 6.3 shows the CO/CO_2 ratio vs. temperature. In general, smoldering alone produces much higher CO/CO_2 ratios (e.g., > 0.2, Tsuchiya, 1994; Malow and Krause, 2008) than is observed in Zone A.

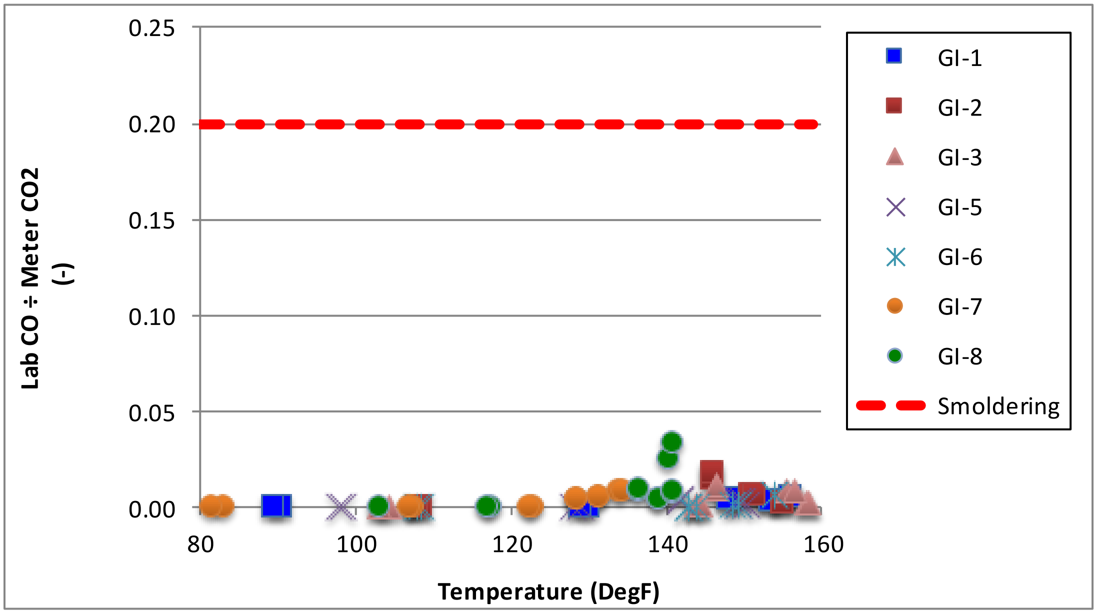


Figure 6.3. *CO/CO_2 ratio vs. temperature at locations with laboratory CO measurements (other locations did not have meter CO concentrations > 100 ppmv). Data is from the third and fourth sampling events that had reliable soil gas data. The highest CO/CO_2 ratios are not correlated to the highest temperatures, and are much lower than the CO/CO_2 ratios seen for smoldering-only systems. See Appendix G for soil gas data.*

Although not definitive alone, these CO relationships support the conclusion that combustion is not occurring in Zone A.

6.3 Why did the Carbon Monoxide Increase in Intermediate Zone SVE Wells?

While the soil gas sampling points show a maximum laboratory CO of 930 ppmv (at location GI2-32), the two SVE wells screened in the intermediate zone exhibit higher concentrations, up to 1400 ppmv, with an increasing trend after Sept. 2016 (see Figure 6.4).

The scientific literature has several examples where non-combustion processes result in high (>1000 ppmv) CO concentrations. Haarstad et al. (2006) cite “suboptimal conditions” during biodegradation, such as:

1. Change from Aerobic to Anaerobic Conditions: Low oxygen levels during aerobic composting. In their laboratory experiments, they were able to generate CO concentrations of 2000 ppmv without any combustion by changing a formerly aerobic process to a deeply anaerobic process.
2. Change from Anaerobic to Aerobic Conditions: Low CH_4 production during anaerobic degradation, where the portion of the microbial community that converts fermentation products to methane stops performing (high temperature, slightly aerobic conditions), resulting in accumulation of carbon monoxide and hydrogen gas.

They wrote:

> *"[t]he 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."*
>
> *"The CO concentrations measured during anaerobic conditions varied from 0 to 3000 ppm."*
>
> *"CO is produced in concentrations ≤6000 ppm by sulfate-reducing bacteria, with substrates such as lactate, pyruvate, formiate, hydrogen, and sulfate."*

Powell et al. (2006) performed a full-scale experiment similar to Haarstad et al.'s Anaerobic to Aerobic process, where air was injected into a deeply anaerobic landfill to convert it to aerobic conditions. During this conversion process, they observed CO concentrations over 1000 ppmv in the landfill. They also measured a significant reduction in CH_4 and observed:

> *"The increase in CO concentration was dramatic and raised concern over the occurrence of waste combustion. Landfill operators have measured CO concentration as an indicator of subsurface landfill fires, as CO is a product of incomplete combustion. Although several thermocouples installed within the waste showed an increase in temperature during air addition, the temperatures measured were of the magnitude expected for aerobic biological decomposition, not combustion (the maximum temperature during testing was below the permit threshold value [**170 °F**].* (Powell et al., 2006) (temperature added).

Barlaz et al. (2016b) discuss how *anaerobic* elevated temperature landfills comprise a very small percentage of municipal landfills, and prescribe the following control measure for these systems: removing gas containing volatile chemicals, hydrogen, and other compounds that feed the heat generating reactions, but without introducing large amounts of air to keep the system anaerobic. They state: *"[r]emoving gas from ETLFs [elevated temperature landfills] is important as the gas contains volatile organics that provide fuel for the reactions."*

At Zone A, significant increases in CO have been observed since September 2016 in VEW-6I and VEW-7I (Figure 6.4). This increase in CO is likely due to Condition 1, where a formally aerobic system has now turned deeply anaerobic due to changes in SVE operations, and does not need to be explained by combustion. As shown in Figure 6.4, the increase in CO in these two wells is strongly correlated to the decline in oxygen.

Introducing air, resuming purging, or operating VEW-6I and VEW-7I at low levels will likely reduce CO levels, although it may take several weeks or longer.

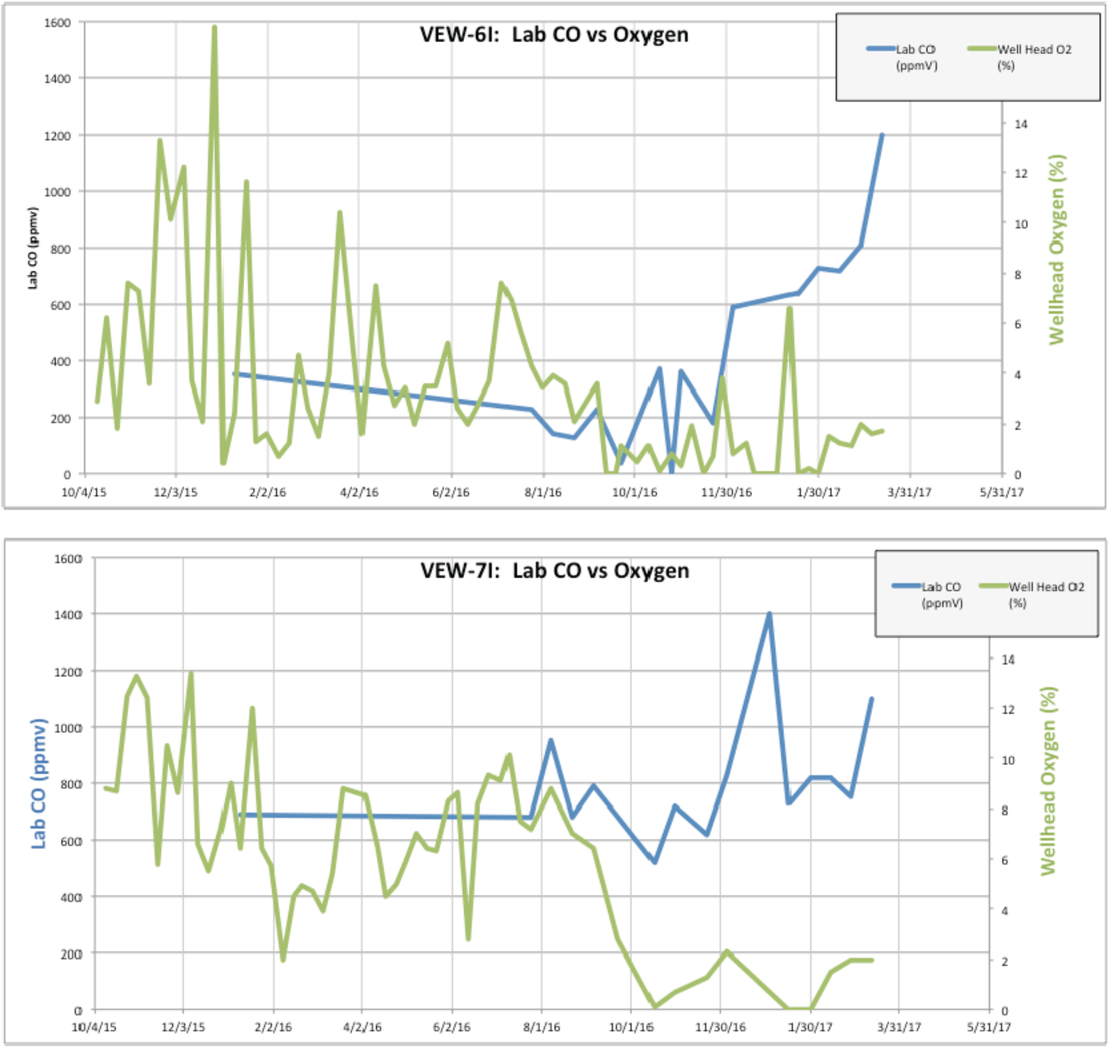


Figure 6.4. *Lab CO and oxygen concentrations in the intermediate zone, Oct. 2015 to March 2017.*

Key Points Specific to Carbon Monoxide

- The highest laboratory analyzed CO measured in the soil gas probes was at location GI6-32 at 930 ppmv. The next highest was GI6-29 at 780 ppmv. Jafari et al. (2017a) use a 1500 ppmv CO threshold as one of four metrics to identify smoldering combustion. Other researchers caution not to use CO as a sole indicator of combustion.

  The CO concentrations in the soil gas sampling points do not indicate combustion in Zone A. While not definitive alone, CO vs. temperature, oxygen, and CO/CO_2 ratios also support the conclusion that combustion is not occurring in Zone A.

- The CO concentrations in VEW-6I and VEW-7I have increased in 2016/2017 to a maximum of 1400 ppmv. This increase is correlated to the decrease of oxygen to very low concentrations (<2%). An increase in CO from non-combustion biological process is expected when an aerobic system is converted to a deeply anaerobic system (Haarstad et al., 2006) and does not indicate combustion.

- Introducing air, resuming purging, or operating VEW-6I and VEW-7I at low levels will likely reduce CO levels, although it may take several weeks or longer.

7.0 CARBON DIOXIDE / OXYGEN RATIO COMPARISON

7.1 Key Principles

Underground combustion of liquids and gases is not self-sustaining in soils containing those contaminants in the pore space. However, solid continuous combustible material, such as municipal solid waste (MSW), can support sustained combustion under the right conditions. An analysis of the relationship of carbon dioxide (CO_2) to oxygen (O_2) was conducted as a line of evidence to evaluate whether the underground oxidation reactions that are consuming oxygen and releasing carbon dioxide, are originating from mixed debris or from organic compounds that may be present in varying concentrations in the soil or debris fill (Table 7.1, Figure 7.1).

Oxidation is a process where oxygen is consumed in a reaction, either by **combustion**, **biodegradation** or more rarely by chemical decomposition (e.g., **pyrolysis**, which occurs at relatively high temperatures, e.g., >390 ºF for wood). The method described in this section assumes relatively complete oxidation to CO_2 with no minor byproducts being produced or accumulated (such as carbon monoxide for combustion or bacteria biomass for biodegradation). Note that combustion can be further subdivided in flaming combustion, or more commonly for municipal landfills, smoldering combustion.

If the results show that the mixed debris is being oxidized, then it is **possible** but not confirmed that combustion is occurring because the mixed debris could instead be biodegrading at a relatively rapid rate. (Section 8.2, however, suggests the mixed waste contains little combustible material).

If the results show that the organic compounds are being oxidized, then it is **unlikely** that combustion is occurring because underground combustion of liquids and gases is not self-sustaining in soils containing contaminants in the pore space.

The method assumes that if no combustion takes place, then the oxygen concentration will be about 21% and the CO_2 concentration will be about 0.03% (atmospheric conditions). This is represented as the far lower right starting point for all the oxidation lines shown on Figure 7.1. If enough oxidation occurs to consume all the oxygen, the amount of CO_2 that is generated depends on the material. As shown in Table 7.1 and Appendix E, if completely oxidation converts the mixed debris to CO_2, then the resulting gas mixture would be ~0% O_2 and between 19-21% CO_2. However, if oxidation converts organic compounds to CO_2, then the resulting gas mixture would be in the 10.5–16% CO_2 range. This is because the molecular formula of components comprising mixed debris is different from that of the organic compounds (see Appendix E). The method does have some uncertainty, and should be given less weight than other combustion metrics such as smoke and temperature.

CO_2 and O_2 concentrations in the soil gas at the 48 soil gas probes at the nine locations (see Figure 3.1 were analyzed (Table 7.2). The data were graphed and compared to standard combustion/biodegradation lines for the two classes of materials as shown in Figure 7.1.

Table 7.1. *Interpretation of CO_2 and O_2 data plotted in Figure 7.2.*

Potential Reactant	Representative Compound	Can Support Self-Sustaining Combustion?	Slope of CO_2/O_2 Stoichiometry Line When Combusted or Biodegraded (see Appendix E)	
Carbonaceous Waste (e.g., Mixed debris)	Wood, Paper, MSW	**Yes.** For example, municipal landfill fires do occur because of continuous nature of MSW.	6 ÷ 6.5 = 0.92 6 ÷ 6 = 1.0 31 ÷ 34 = 0.91	**0.9 to 1.0**
Organic compounds*	Toluene 2-Butanone Methane**	**No** - if the contaminants are present in porous media such as soil. For example, thermal remediation projects do not consider underground fires a concern if the waste material is in soils.	7 ÷ 9 = 0.78 4 ÷ 5.5 = 0.73 1 ÷ 2 = 0.5	**0.5 to 0.78**

** The most common organic compounds in Zone A are aromatics (such as toluene) and ketones (such as 2-butanone); as such, their mass dominates in this analysis.*

*** Methane included because it can only be produced by biodegradation, not combustion.*

7.2 CO_2/O_2 Results

As shown on Figure 7.1 and Table 10-1, almost all the locations with significant oxygen depletion (< 15% oxygen remaining) had a CO_2/O_2 signature of chemical oxidation rather than oxidation of mixed debris. This indicates that most of the oxidation reactions removing oxygen from the soil gas in Zone A are due to oxidation of the chemical contaminants, most likely aerobic biodegradation of the VOCs like toluene and 2-butanone and methane.

The only exception was location GI4, were oxygen levels at several depths were very low but with CO_2/O_2 signatures that represented oxidation of carbonaceous waste such as paper, wood, and MSW characteristic of the mixed debris. At this location, the VOCs in the soil gas were relatively low < ~1000 ppmv (Appendix F) so chemical oxidation was a smaller part of the over oxidation reactions. GI9 showed a combination of mixed debris and chemical oxidation.

The other locations showing mixed debris being the dominant oxidation reaction (TC8, TC9) had very low oxygen depletion and overall are not contributing a large fraction of the oxygen demand at the site.

In addition, 7 of the 15 soil gas probes along the centerline of Zone A (cross section C-C' as shown in Figure 3.1; also see the tan shading in Table ES-2) have oxygen concentrations below the 3% level which has been cited as the minimum threshold that can support smoldering combustion (e.g., U.S. Navy, 1998) and well below the 10-14% level that can support flammable combustion. This supports the conclusion that large-scale combustion is not occurring in Zone A.

Key Points Specific to Carbon Dioxide/Oxygen Ratio

- Overall the Zone A CO_2/O_2 data indicate that most areas with significant oxygen depletion have the gas signature of organic chemicals that are being oxidized, not mixed debris.
- Because underground combustion of liquids and gases is not self-sustaining in soils, these results support the conclusion that there is no underground combustion occurring in Zone A.

Table 7.2. *Soil Gas Sampling Data*.

Sampling Location	Sampling Depth (ft bgs)	Sampling Date: 22-Feb-17		Sampling Date: 28-Feb-17	
		CO_2 (%)	O_2 (%)	CO_2 (%)	O_2 (%)
GI1	7	0.2	20.9	0.1	21.5
GI1	14	3.1	16.7	1.7	18.8
GI1	24	5.6	14.5	5	15.3
GI1	29	12.3	5.8	12.2	5.8
GI1	35	12.2	5.7	12	5.9
GI2	8	5.8	15.1	5.7	14.1
GI2	16	13.6	2.1	12.6	3.6
GI2	27	12.4	2	12	3.3
GI2	32	4.3	11.4	4.1	12.1
GI2	36	1.3	17.4	1.2	17.4
GI3	8	0.4	20.8	2.5	18.3
GI3	16	14.4	0.3	14.1	0.4
GI3	25	13.7	0.3	12.9	1.5
GI3	30	2.8	14.4	2	17.1
GI3	37	3.7	10.8	2.1	14.7
GI4	9	1.5	20.3	1.6	18.2
GI4	14	14.2	6.2	13.5	5.3
GI4	19	17.3	2.3	17.5	1.7
GI4	24	19	1.1	19.1	0.4
GI4	30	18.9	0.5	18.7	0.2
GI5	7	0.8	19.9	0.6	20.5
GI5	12	4.6	15.5	4.6	15.6
GI5	21	8.4	5.7	7.5	7.3
GI5	28	13	0.3	12.1	0.7
GI5	33	13.2	0.3	11.3	2.5
GI6	12	1.3	19.5	1.4	19.2
GI6	22	13.9	0.4	14.1	0.4
GI6	25	13.5	0.4	13.9	0.3
GI6	29	12.3	1.6	12.3	1.7
GI6	36	13.4	0.5	13.6	0.5
GI7	8	1.5	20.4	1.3	19.8
GI7	17	3.5	17.6	3.5	17
GI7	23	4.8	15.1	4.5	15.4
GI7	26	2.9	14.8	2.9	15.1
GI7	29	5.8	12.7	5.6	13.6
GI7	33	3.1	14.2	3.4	13.1
GI8	13	0.7	21.4	0.7	20.3
GI8	17	2.6	18.8	2.5	18.2
GI8	26	1.9	19.4	1.6	19.2
GI8	29	2.8	18.6	2.2	18.4
GI8	32	1.2	18	0.9	17.7
GI8	37	4.7	14.5	4	15.2
GI9	19	5.3	16	5	16.5
GI9	25	1.5	19.6	1	20.2
GI9	29	1.8	19.1	1.7	19.3
GI9	34	2.7	18.1	2.7	18
GI9	39	2.9	18.2	2.8	17.9

CO_2 = carbon dioxide; ft bgs = feet below ground surface; O_2 = oxygen.

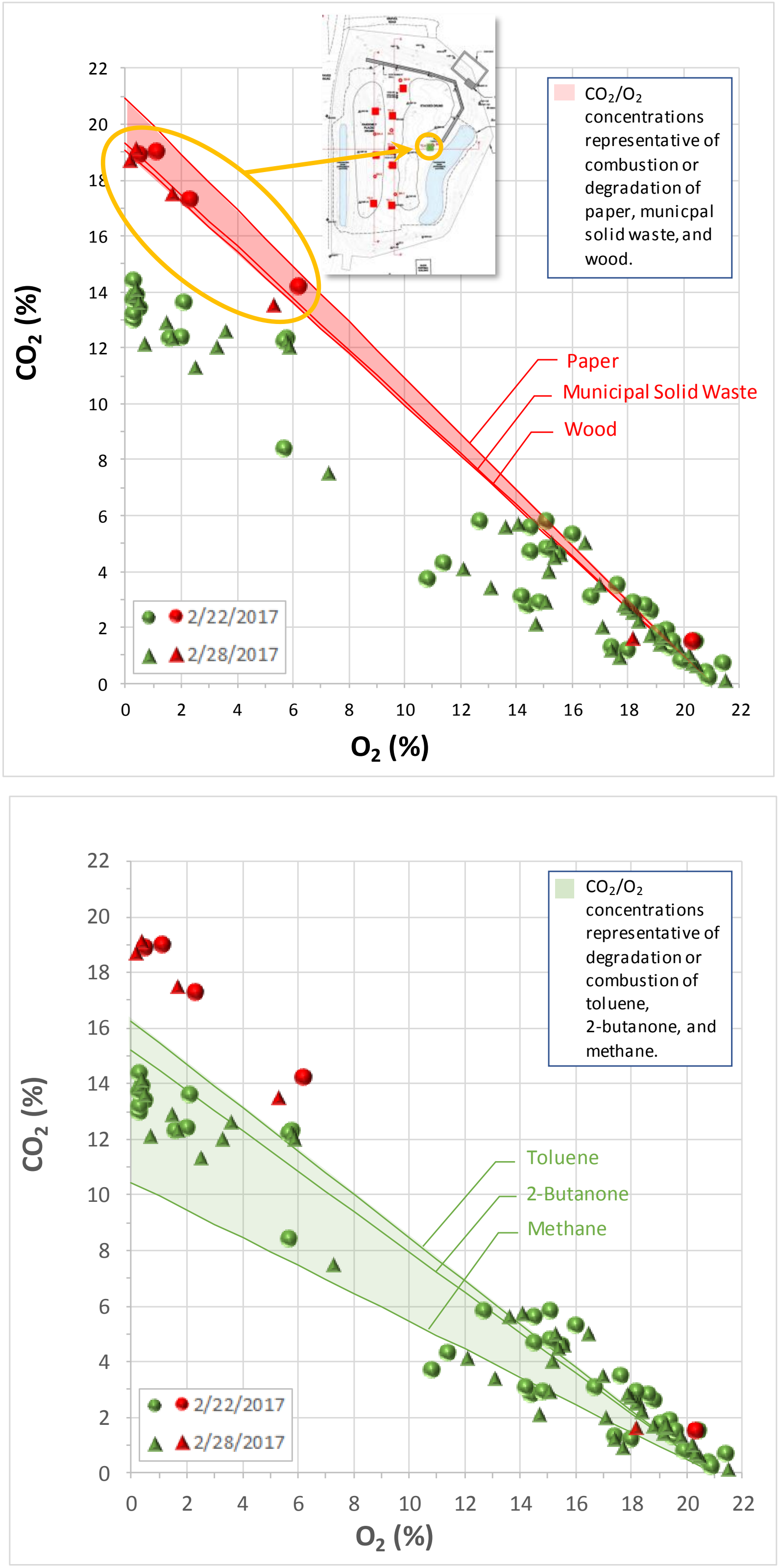


Figure 7.1. *Comparison of Zone A soil gas data with degradation/combustion regression lines. Red dots are from Location TC4, green dots are all other locations.* ***Top Panel:*** *Comparison with MSW, paper, and wood.* ***Bottom Panel:*** *Comparison with toluene, 2-butanone, and methane.*

8.0 CHARACTERISTICS OF "MIXED DEBRIS" AND TVS ANALYSIS

The following sub-sections present the methods used to determine the relative presence and content of the mixed debris encountered, the process to collect the samples for TVS analysis, and the key findings for comparisons between the many logs available for analysis, and each of the large diameter borings.

8.1 Methods

During the drilling process described in Section 4, recovered materials were inspected by SCS personnel. Recovered materials were classified using a modified version of the Unified Soil Classification System (USCS). A key to the modified USCS used by SCS is provided in Appendix C. Modification to the USCS was required to include mixtures of the encountered soils and refuse, referred to as mixed debris, that are typical within landfill environments.

Recovered materials from the borings were logged as described in the Work Plan. Following recovery of the materials by the Driller the follow events occurred (in order):

a. The soil temperature was measured using an IR thermometer.
b. The recovery was photographed. When the core barrel tooling was used, the process described in Section 4.1 was used to dislodge the bottom section of recovery for documentation.
c. The Driller's assistant spread the sample out within the containment area for SCS personnel to classify and document the recovery.
d. Samples of the mixed debris encountered were collected as directed by SCS personnel, if desired or as conditions warranted.
e. The recovered materials were containerized for disposal or stockpiled for backfill of the boring as directed by SCS.

Where refuse was encountered, the composition of the refuse (e.g. wood, metal, plastics, and textiles) was documented, as well as the relative percent composition (by volume) with respect to the remainder of the section of the recovery being logged. At the discretion of SCS personnel two to six bulk bag samples were collected from each boring within the mixed debris layer(s). At the end of each day, up to three samples were collected and field preserved for each boring from within the layer(s) of mixed debris encountered. Samples were field preserved in 8-ounce soil jars and put on ice, and kept at a temperature below 6.0°C (42.8°F) consistent with USEPA method SM 2540 for total, fixed, and volatile solids in water, solids, and biosolids. Locations of the samples collected are presented on the boring logs in Appendix C. A summary table of the collected samples is presented below (Table 8.1).

Table 8.1: *TVS sample collection summary*

Well Designation	BA-1	BA-2	BA-3	BA-4	BA-5	BA-6
Sample No. 1 Depth (ft)(1)	20	26.3	23	26	17	28.5
Sample No. 2 Depth (ft)(1)	22	28	26	28.5	23.5	32
Sample No. 3 Depth (ft)(1)	30	30	29	30	30	NA

Notes:
1. All depths recorded as reported by the Driller, unless noted otherwise.
2. NA = Not Applicable. No sample collected.

At the discretion of SCS personnel, a third sample was not collected from boring BA-6 as the subsurface conditions did not warrant an additional sample due to the lack of sufficient mixed debris. The lens of mixed debris encountered was relatively thin with little variation, as opposed to what was observed in the other borings.

Samples collected by SCS were relinquished to Environmental Partners Inc. (EPI) personnel on the final day of drilling, February 16, 2017, for submittal to Analytical Resources, Incorporated (ARI) for analysis. Results from the sample analysis are shown on the boring logs in Appendix C.

8.2. Total Volatile Solids Results

Results from the sample analysis are shown on the boring logs (Appendix C.) at the location where the samples were obtained. The results of the TVS analyses prepared by ARI are also presented in Appendix C. A summary table of the laboratory results for TVS is presented below.

Table 8.2: *TVS Analytical Results Summary (percent by weight)*

Well Designation		BA-1	BA-2	BA-3	BA-4	BA-5	BA-6
Sample No. 1	% by weight	21.1	8.07	8.08	3.00	9.63	13.3
	depth	20 ft	26.3 ft	23 ft	25.5 ft	17 ft	28.5 ft
Sample No. 2	% by weight	6.90	22.7	20.2	16.6	4.88	14.4
	depth	22 ft	28 ft	26 ft	28 ft	23.5 ft	32 ft
Sample No. 3	% by weight	5.22	28.5	8.17	6.53	1.56	NA
	depth	30 ft	30 ft	29 ft	29.5 ft	30 ft	--
Average (%)	--	11.1	19.8	12.2	8.71	5.36	13.9

Notes:
1. NA = Not Applicable. No sample collected.

The values for TVS presented represent the percentage of the sample that is unburnt or that is unspent organic content within the sample collected. Organic content within the sample can be from buried refuse within the sample or from the organic content of the disposed soils. The TVS value can be correlated to the volume of material that can support combustion within the sample.

Using the results of the TVS analyses, the volume of volatile material (susceptible combustion) within each boring was determined. The TVS result obtained was applied to the range of mixed debris material associated with that sample. For example, in BA-1, the upper TVS sample was obtained at 20 feet below ground surface, the second sample was obtained at 22 feet below ground surface, and the third one was obtained at a depth of 30 feet below ground surface. The range for BA-1 20’ would be from the depth where the mixed debris was first encountered (17 feet) to the midpoint between samples BA-1 20’ and BA-1 22’, or 21 feet below ground surface. Using the same rationale, the range for BA-1 22’ was determined to be from the midpoint between samples BA-1 20’ and BA-1 22’, to the midpoint between BA-1 22’ and BA-1 30’, or from 21 feet to 26 feet below ground surface and the range for BA-1 30” was from 26 feet to the bottom of the mixed debris layer (37 feet below ground surface). The volume of the mixed debris material within the boring for each pass of the boring tooling is determined and is multiplied by the percentage of refuse and wood debris content, as documented in the boring logs, to determine volume of mixed debris in each section of the boring. The TVS analytical result is applied to the volume of mixed debris to determine volume the volatile material within the layer of mixed debris. Once the volume for each layer of mixed debris is determined, a total volume of volatile material is determined for the length of the boring in which mixed debris was encountered. This method was applied to each of the large diameter boring to determine the volume of TVS. Using this analysis, it was determined that the mixed debris layer, as observed in the large diameter borings, contains an average of about 11.4 percent TVS. In addition, the average TVS content of the entire depth of each boring combined is 0.8 percent. A summary of the TVS content in the borings is presented in Table 8.3. On average, MSW has an average TVS content of 50 percent. Compared to MSW, the mixed debris layer is significantly lower (50% vs 11.4%). Over the entire thickness of the combined borings compared to MSW, the TVS content within the boring is substantially lower (50% vs 0.8%). Tables of the TVS content calculation for each of the large diameter borings is included in Appendix C.

Table 8.3: *TVS Content Summary of Boring*

Boring	BA-1	BA-2	BA-3	BA-4	BA-5	BA-6	Total	Site Average
Total Depth (ft)	38.0	35.0	36.0	35.0	34.0	36.0	214.0	35.7
Total Volume of Boring (ft^3)	119.4	110.0	113.1	110.0	106.8	113.1	672.3	112.1
Total Volume of Mixed Debris (ft^3)	11.7	1.4	13.2	0.5	15.0	7.5	49.3	8.2
Total Volume of TVS (ft^3)	1.1	0.3	1.9	0.0	1.0	1.0	5.2	0.9
Volume of Boring as Mixed Debris (%)	9.8	1.3	11.7	0.4	14.1	6.6	7.3	7.3
Volume of Mixed Debris as TVS (%)	9.3	19.2	14.1	6.0	6.6	13.1	10.6	11.4
Volume of Boring as TVS (%)	0.9	0.3	1.6	0.0	0.9	0.9	0.8	0.8

8.3 Continuity of the Mixed Debris

The degree of continuity of the mixed debris observed in Zone A is also a critical factor in assessing the potential for combustion:

- If there are thick, continuous layers of combustible mixed debris then the potential for combustion is higher;
- If the mixed debris is in thinner, discontinuous layers then the potential for subsurface combustion is greatly reduced.

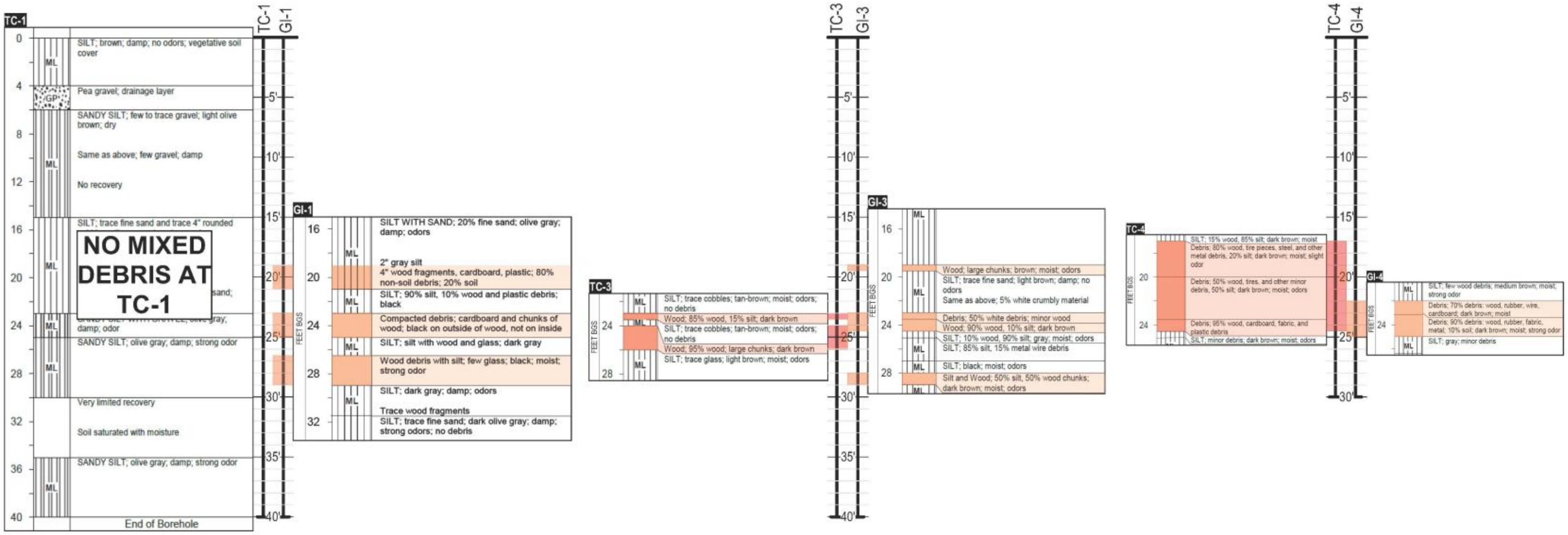
One method to evaluate the mixed debris layer is based on the first observation that mixed debris was variably present in seven of the nine borings (Figures 3.2a, 3.2b, and 3.2c), and it did not appear to represent homogenous, extensive, or contiguous layers or particularly large masses of debris. This method offers an initial large-scale comparison over a 40 to 60 foot horizontal distance. Overall, the mixed debris appeared sporadically (i.e., without much of a pattern) in only seven of the nine locations.

A short-scale comparison over a 5-foot horizontal distance provides a slightly better perspective. By first comparing the presence of mixed debris shown in the thermocouple borings vs. the soil gas borings, a small-scale comparison over five horizontal feet can be made (Figures 8.1a, b, c, and d). Several of many possible examples follow. A visual inspection of the logs shows the mixed debris in GC1 is not present 5 feet away in TC1 (Figure 8.1a). The relatively thick layer in TC-4 is much thinner only 5 feet away in GI4 (Figure 8.1a). And the three thin layers of mixed debris in GI6 do not correlate vertically to a thicker zone of mixed debris 5 feet away in TI4. Overall these and other comparisons support the conclusion that the mixed debris is generally in thin and somewhat discontinuous lenses that would not support or propagate sustained combustion if it should occur in the subsurface.

Key Points Specific to the Occurrence of Mixed Debris

- Results of the TVS analysis from the large diameter borings indicate that a significant portion of the fill within Zone A of the landfill is not volatile. When viewed in conjunction with the prepared boring logs, the lenses of mixed debris encountered were separated by layers of silty sand and/or sandy silts with little to no organic content.
- Samples collected from the borings where a significant portion of the recovery was described as refuse or mixed debris (<30% by volume), did not have a TVS result proportionate to that of the recovered materials described. The lower TVS result for the mixed debris (11.4 %) can be attributed to the refuse and mixed debris recovered being decomposed and no longer combustible.
- The mixed debris occurs in generally thin and discontinuous lenses, even over short distances making sustained combustion or the propagation of unlikely.

TYPICAL DISTANCE BETWEEN THERMOCOUPLE AND SOIL GAS BORINGS: 5 FEET



0 6.25 12.5 25

HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 75' (3X EXAGGERATION)

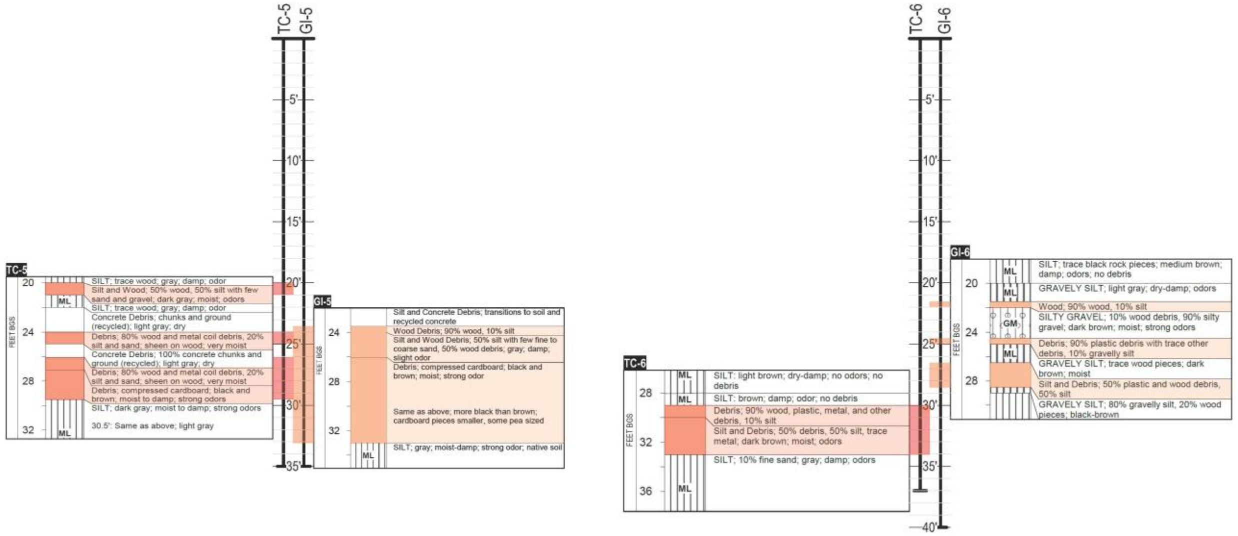
NOTES:

🟥	>50% NON-SOIL IN TCs
🟧	>50% NON-SOIL IN GIs

FIGURE 8.1A
TC & GI PAIRS WITH BORING LOG EXCERPTS
AND DEPTH INTERVALS SHOWING >50% NON-SOIL

PREPARED BY	ENVIRONMENTAL PARTNERS INC		
REPORT	CROSS SECTIONS		
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON		
PREPARED FOR	IWAG GROUP III		
DATE 4/24/17	***DRAWN BY*** VPB	***REVIEWED BY*** ARM	***PROJECT NUMBER*** 03916.0

TYPICAL DISTANCE BETWEEN THERMOCOUPLE AND SOIL GAS BORINGS: 5 FEET



0 6.25 12.5 25

HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 75' (3X EXAGGERATION)

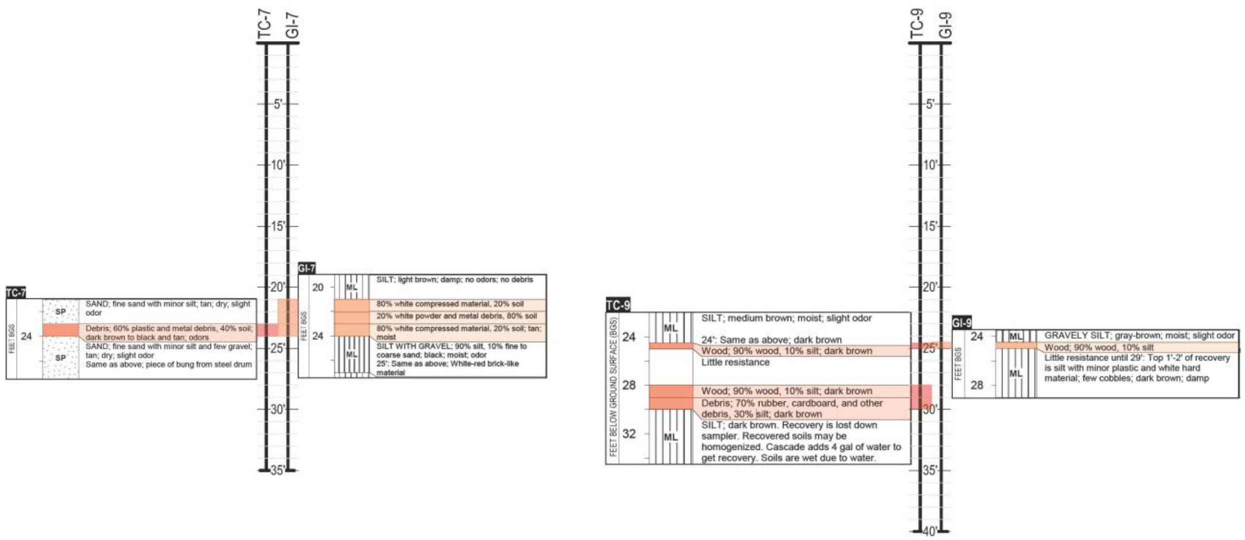
NOTES:

🟥 >50% NON-SOIL IN TCs
🟧 >50% NON-SOIL IN GIs

FIGURE 8.1B
TC & GI PAIRS WITH BORING LOG EXCERPTS
AND DEPTH INTERVALS SHOWING >50% NON-SOIL

PREPARED BY	epi ENVIRONMENTAL PARTNERS INC		
REPORT	CROSS SECTIONS		
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON		
PREPARED FOR	IWAG GROUP III		
DATE 4/24/17	***DRAWN BY*** VPB	***REVIEWED BY*** ARM	***PROJECT NUMBER*** 03916.0

TYPICAL DISTANCE BETWEEN THERMOCOUPLE AND SOIL GAS BORINGS: 5 FEET



0 6.25 12.5 25

HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 75' (3X EXAGGERATION)

NOTES:

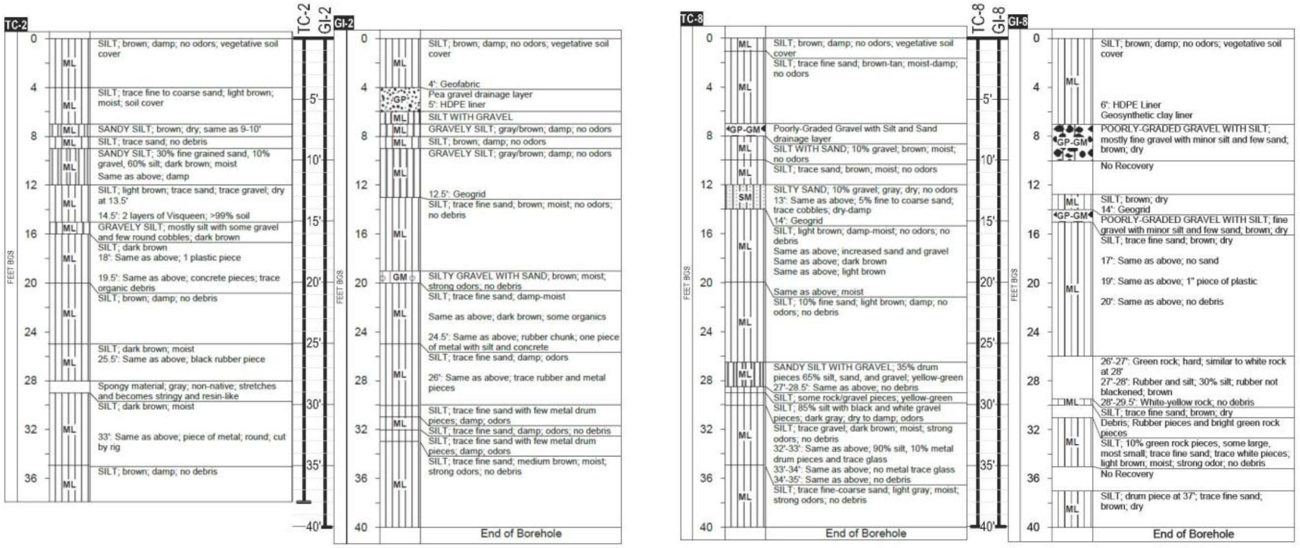
🟥 >50% NON-SOIL IN TCs

🟧 >50% NON-SOIL IN GIs

FIGURE 8.1C
TC & GI PAIRS WITH BORING LOG EXCERPTS
AND DEPTH INTERVALS SHOWING >50% NON-SOIL

PREPARED BY	ENVIRONMENTAL PARTNERS INC		
REPORT	CROSS SECTIONS		
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON		
PREPARED FOR	IWAG GROUP III		
DATE 4/24/17	***DRAWN BY*** VPB	***REVIEWED BY*** ARM	***PROJECT NUMBER*** 03916.0

TYPICAL DISTANCE BETWEEN THERMOCOUPLE AND SOIL GAS BORINGS: 5 FEET



TC-2

SILT; brown; damp; no odors; vegetative soil cover
SILT; trace fine to coarse sand; light brown; moist; soil cover
SANDY SILT; brown; dry; same as 9-10'
SILT; trace sand; no debris
SANDY SILT; 30% fine grained sand, 10% gravel, 60% silt; dark brown; moist
Same as above; damp
SILT; light brown; trace sand; trace gravel; dry at 13.5'
14.5': 2 layers of Visqueen; >99% soil
GRAVELY SILT; mostly silt with some gravel and few round cobbles; dark brown
SILT; dark brown
18': Same as above; 1 plastic piece
19.5': Same as above; concrete pieces; trace organic debris
SILT; brown; damp; no debris
SILT; dark brown; moist
25.5': Same as above; black rubber piece
Spongy material; gray; non-native; stretches and becomes stringy and resin-like
SILT; dark brown; moist
33': Same as above; piece of metal; round; cut by rig
SILT; brown; damp; no debris

GI-2

SILT; brown; damp; no odors; vegetative soil cover
4': Geofabric
Pea gravel drainage layer
5': HDPE liner
SILT WITH GRAVEL
GRAVELY SILT; gray/brown; damp; no odors
SILT; brown; damp; no odors
GRAVELY SILT; gray/brown; damp; no odors
12.5': Geogrid
SILT; trace fine sand; brown; moist; no odors; no debris
SILTY GRAVEL WITH SAND; brown; moist; strong odors; no debris
SILT; trace fine sand; damp-moist
Same as above; dark brown; some organics
24.5': Same as above; rubber chunk; one piece of metal with silt and concrete
SILT; trace fine sand; damp; odors
26': Same as above; trace rubber and metal pieces
SILT; trace fine sand with few metal drum pieces; damp; odors
SILT; trace fine sand; damp; odors; no debris
SILT; trace fine sand with few metal drum pieces; damp; odors
SILT; trace fine sand; medium brown; moist; strong odors; no debris
End of Borehole

TC-8

SILT; brown; damp; no odors; vegetative soil cover
SILT; trace fine sand; brown-tan; moist-damp; no odors
Poorly-Graded Gravel with Silt and Sand drainage layer
SILT WITH SAND; 10% gravel; brown; moist; no odors
SILT; trace sand; brown; moist; no odors
SILTY SAND; 10% gravel; gray; dry; no odors
13': Same as above; 5% fine to coarse sand; trace cobbles; dry-damp
14': Geogrid
SILT; light brown; damp-moist; no odors; no debris
Same as above; increased sand and gravel
Same as above; dark brown
Same as above; light brown
Same as above; moist
SILT; 10% fine sand; light brown; damp; no odors; no debris
SANDY SILT WITH GRAVEL; 35% drum pieces 65% silt, sand, and gravel; yellow-green
27'-28.5': Same as above; no debris
SILT; some rock/gravel pieces; yellow-green
SILT; 85% silt with black and white gravel pieces; dark gray; dry to damp; odors
SILT; trace gravel; dark brown; moist; strong odors; no debris
32'-33': Same as above; 90% silt, 10% metal drum pieces and trace glass
33'-34': Same as above; no metal trace glass
34'-35': Same as above; no debris
SILT; trace fine-coarse sand; light gray; moist; strong odors; no debris
End of Borehole

GI-8

SILT; brown; damp; no odors; vegetative soil cover
6': HDPE Liner
Geosynthetic clay liner
POORLY-GRADED GRAVEL WITH SILT; mostly fine gravel with minor silt and few sand; brown; dry
No Recovery
SILT; brown; dry
14': Geogrid
POORLY-GRADED GRAVEL WITH SILT; fine gravel with minor silt and few sand; brown; dry
SILT; trace fine sand; brown; dry
17': Same as above; no sand
19': Same as above; 1" piece of plastic
20': Same as above; no debris
26'-27': Green rock; hard; similar to white rock at 28'
27'-28': Rubber and silt; 30% silt; rubber not blackened; brown
28'-29.5': White-yellow rock; no debris
SILT; trace fine sand; brown; dry
Debris; Rubber pieces and bright green rock pieces
SILT; 10% green rock pieces, some large, most small; trace fine sand; trace white pieces; light brown; moist; strong odor; no debris
No Recovery
SILT; drum piece at 37'; trace fine sand; brown; dry
End of Borehole

NO MIXED DEBRIS AT THESE LOCATIONS

0 6.25 12.5 25

HORIZONTAL SCALE: 1" = 25'
VERTICAL SCALE: 1" = 75' (3X EXAGGERATION)

NOTES:

🟥	>50% NON-SOIL IN TCs
🟧	>50% NON-SOIL IN GIs

FIGURE 8.1D
TC & GI PAIRS WITH BORING LOG EXCERPTS AND DEPTH INTERVALS SHOWING >50% NON-SOIL

PREPARED BY	ENVIRONMENTAL PARTNERS INC		
REPORT	CROSS SECTIONS		
LOCATION	PASCO LANDFILL NPL SITE 1901 DIETRICH ROAD, PASCO, WASHINGTON		
PREPARED FOR	IWAG GROUP III		
DATE 4/24/17	***DRAWN BY*** VPB	***REVIEWED BY*** ARM	***PROJECT NUMBER*** 03916.0

9.0 GAS AUTOIGNITION TEMPERATURE

The Work Plan states: "*[t]he autoignition temperature of the gas mixture in the subsurface at Zone A is a valuable parameter to help gauge the overall risk of an autoignition event.*"

A two-step approach for collecting the 3-liter gas sample required for autoignition testing is being used to select the location of the gas sample. The goal of the two step approach is to find a location that represents a relatively high probability for low temperature autoignition at the site.

> **Step 1:** Review soil gas data to determine locations for more detailed VOC testing. Select several locations based on high hydrocarbon concentrations (based on PID), high Lower Explosive Limit (LEL) data, and relatively high oxygen levels that will support potential combustion.
>
> **Step 2:** After analyzing the VOC data, select the location for autoignition testing. The presence of low-autoignition constituents such as carbon disulfide will be considered in the selection process.

Step 1 and Step 2 has been completed with the results shown in Table 9.1. Using these data location **GI2-32** have been selected for providing the gas sample for autoignition testing.

Table 9.1. *Locations for Step 2 VOC sampling to select location for autoignition testing. Note PID and Total VOCs reported in different units. GI2-32 has been selected for the autoignition sampling.*

Location	O_2 (%)	PID (ppmV)	LEL (%)	Total VOCs (µg/L)	Carbon Disulfide (µg/L)
GI2-32	10.3	>9,999	100	18,474	0.36
GI1-35	6.1	>9,999	100	18,413	1.4
GI3-25	0.3	5,153	100	17,452	ND
GI2-27	1.8	9,999	56	14,118	0.3
GI5-28	0.2	4,794	72	11,907	0.46
GI8-37	14.7	4,894	20	7,868	0.35
GI6-29	0.9	3,079	20	6,869	1.4
GI4-30	0.2	768	60	3,349	ND

Key Points Specific to Autoignition Testing

- Autoignition testing on gas collected from Zone A will be conducted to confirm that autoignition is not an issue of concern.
- The location selection process for collecting the autoignition sample has been completed. The actual sample collection and analysis will happen in April/May 2017.

10.0 CONCLUSIONS AND RECOMMENDATIONS

10.1 Results

Seven lines of evidence were independently developed to evaluate potential for subsurface combustion in Zone A: smoke, in-situ soil temperatures, carbon monoxide, characteristics of the mixed debris, Total Volatile Solids analysis of the mixed debris, carbon dioxide/oxygen relationship, and autoignition testing. All but the autoignition test have been completed.

Table 10.1 provides a summary of the combustion lines of evidence data generated by the testing program by monitoring location.

The data show these results:

- During the drilling process smoke was not observed in any of the borings. No signs of ongoing subsurface combustion were identified, including soil core temperatures in excess of 170°F.
- Overall, the maximum temperatures seen at in the 46 operational thermocouples in Zone A were 159 ºF during the main test period (and 160 ºF during a subsequent six-day test period). These temperatures are not indicative of current combustion in Zone A.
- The CO concentrations in the 47 soil gas sampling points showed a maximum of 930 ppmv and do not indicate current combustion in Zone A.
- The CO concentrations in VEW-6I and VEW-7I increased in 2016/2017 and realized a maximum of 1400 ppmv. This increase is correlated with the decrease in oxygen levels to very low concentrations (<2% oxygen) (attributable to the cessation of SVE purging of the intermediate wells). An increase in CO from non-combustion biological process is expected when an aerobic system is converted to a deeply anaerobic system (Haarstad et al., 2006) and can explain why CO is increasing in these areas of Zone A.
- Overall, the Zone A CO_2/O_2 data indicate that it is primarily organic compounds that are being oxidized in most of Zone A, and not the mixed debris through combustion or biodegradation. Because underground combustion of liquids and gases is not self-sustaining (if it could occur at all) in soils containing contaminants in the pore space, these results support the conclusion that there is no underground combustion occurring in Zone A. In a similar manner, combustion is not likely to occur in Zone A in the future.
- The lenses of mixed debris in Zone A are separated by layers of silty sand and/or sandy silt with little to no organic content and are not continuous across the site or even relatively short distances. Results of the TVS analysis from the large diameter borings indicate that a significant portion of the fill within Zone A of the landfill is not volatile, and therefore the combustion potential is relatively low.

Table 10-1. *Summary of lines of evidence data for key locations in Zone A.*

Cross-Section	Location	1. Visual Observation of Smoke	2. Maximum *In situ* Soil Temperature (°F)	3. Average Lab Carbon Monoxide Concentration ** (ppmv)	4. Average PID (ppmv)	4. Average Oxygen (%)	4. Material Being Oxidized Based on Carbon Dioxide/Oxygen Relationship	5. Characteristics/Thickness of Mixed Debris (MD) Layer. TC: Thermocouple Boring; GC: Gas Concentration Boring located ~ 5 feet away.			6. Total Volatile Solids (TVS) in Mixed Debris / Entire Boring	Combustion Indicated?
								TC Borings	Overlap	GC Borings		
C	TC/GI1-24	None	157	295	1,725	15	Combination	No mixed debris	0'	6.5' (3 layers)	BA-1 9.3% / 0.9%	No
C	TC/GI1-29	None	154	445	4,741	6	Combination					
C	TC/GI1-35	None	148	480	5,112	6	Combination					
C	TC/GI2-27	None	154	295	**7,481**	3	Chemicals	No mixed debris	0'	No mixed debris		No
C	TC/GI2-32	None	152	280	6,174	12	Chemicals					
C	TC/GI2-36	None	146	200	4,512	17	Chemicals					
C, B	TC/GI3-25	None	**159***	280	4,558	1	Chemicals	2.5' (1 layer)	1'	3' (3 layers)	BA-3 14.1% / 1.6%	No
C, B	TC/GI3-30	None	157	205	4,504	16	Chemicals					
C, B	TC/GI3-37	None	147	295	3,756	13	Chemicals					
C	TC/GI5-21	None	143	295	3,479	7	Chemicals	5.5' (3 layers)	4.5'	9.5' (1 layer)		No
C	TC/GI5-28	None	150	305	4,474	1	Chemicals					
C	TC/GI5-33	None	151	280	4,585	1	Chemicals					
C	TC/GI6-25	None	150	160	3,357	0.4	Chemicals	4 (1 layer)	0'	3' (3 layers)	BA-6 13.9% / 0.9%	No
C	TC/GI6-29	None	153	**765****	3,372	2	Chemicals					
C	TC/GI6-36	None	143	41	3,719	1	Chemicals					
B	TC/GI4-19	None	123	*<100 (meter)*	*1,063*	2	Mixed Debris	7.5' (1 layer)	1	3' (1 layer)	BA-5 6.6% / 0.9%	No
B	TC/GI4-24	None	125	*<100 (meter)*	*745*	1	Mixed Debris					
B	TC/GI4-30	None	124	*<100 (meter)*	*892*	0.4	Mixed Debris					
A	TC/GI7-23	None	123	*<100 (meter)*	*804*	15	Combination	1' (1 layer)	1'	3' (1 layer)	BA-2 19.2% / 0.3% BA-4; 13.1% / 0.9%	No
A	TC/GI7-26	None	129	120	1,507	15	Chemicals					
A	TC/GI7-29	None	132	320	2,997	13	Chemicals					
A	TC/GI7-33	None	135	285	2,266	14	Chemicals					
A, B	TC/GI8-26	None	139	78	1,427	19	Mixed Debris	No mixed debris	0'	No mixed debris		No
A, B	TC/GI8-29	None	141	190	3,668	19	Mixed Debris					
A, B	TC/GI8-32	None	141	300	3,530	18	Chemicals					
A, B	TC/GI8-37	None	137	385	4,173	15	Chemicals					
A	TC/GI9-25	None	119	118	*616*	20	Mixed Debris	2.5' (2 layers)	0.5'	0.5' (1 layer)		No
A	TC/GI9-29	None	124	*<100 (meter)*	*641*	19	Mixed Debris					
A	TC/GI9-34	None	129	*<100 (meter)*	*797*	18	Mixed Debris					
A	TC/GI9-39	None	126	*<100 (meter)*	*879*	18	Mixed Debris					

* 160 °F measured during subsequent Six Day test ** 930 ppmv measured in Sample Event 1 at GI2-32.

10.2 Conclusion

In summary, 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, if implemented in a controlled, data-driven manner as discussed below.

10.3 Recommendations

Moving forward, the IWAG will complete the autoignition testing program for Zone A soil gas, as the last line of field evidence in this evaluation. It should be noted, however, that the composition and condition of the soil gas measured in Zone A do not suggest that autoignition of the gas is a concern at Zone A.

In addition, we recommend the following be applied as part of the on-going operation of the Zone A SVE system to monitor and assess critical parameters informing the conceptual site model.

- Continued monitoring temperature, particularly of the thermocouple locations that had small (≤ 5 ºF) increases in temperature during the testing program, with the recent re-programming of the dataloggers to measure temperature from Type T thermocouples from this point forward. Investigative work should be conducted to determine if the one inoperative thermocouple (TC2-16) can be brought back in service or otherwise be replaced if necessary.
- Track the shallow versus deep temperature thermocouple data to discern temperature fluctuations due to seasonal heating and significant barometric effects.
- Apply current landfill research that cautions against relying on single lines of evidence, particularly carbon monoxide alone, to assess subsurface combustion:
    - Barlaz et al. (2016) states "*[n]onetheless, concluding that a landfill is "on fire" based on elevated temperatures and elevated CO concentrations can be erroneous" and "Consequently, ETLFs often exhibit elevated temperatures and elevated CO concentrations, even though a landfill fire (combustion) is not present*."
    - Jafari et al. (2017a) advocated using these three criteria together for finding a "smoldering front": CO >1500 ppmv, and ratio of CH_4 to CO_2 less than 0.2; and in-situ waste temperatures >80 °C (176 °F). They concluded temperature was the most of these accurate metrics. Finally, they stressed that the "tail" of a smoldering front can be identified by high settlement rates (> 3% per year).
- Resume operation of the intermediate zone SVE wells after installation of the new RTO and upgraded monitoring and control system in a staged manner and carefully evaluate how soil gas concentrations and in-situ temperatures respond. Incorporate soil gas and vapor temperature data into the operational decisions for the SVE system to determine and calibrate the response of the Zone A system under different flowrate conditions.
- The consultant team has a high degree of confidence in our conclusions from the combustion study and believes data collection for implementation of the recommendations can be performed in the current periodic manner using discrete sample events. However, IWAG has advised they will evaluate and implement, if feasible, enhanced data collection methods with extraction from the intermediate wells to provide Ecology with additional assurances that operation of these wells would not result in combustion. One enhancement could be to implement continuous temperature monitoring of the in-situ soil thermocouples

and vapor from the intermediate wells with the data used as control parameters by the SVE process control system so as to rapidly identify any significant changes in the subsurface. The temperature monitoring data could be compared with other parameters relied upon in the recent landfill combustion literature to evaluate the conditions under which potential combustion could occur.

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