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DEPARTMENT OF ECOLOGY
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September 5, 2017

Mr. Michael Riley
Principal
Anchor QEA, LLC
101 North Capital Way, Suite 107
Olympia, WA 98501

Re: Pasco Landfill – Ecology Response to Industrial Waste Area Group (IWAG) Zone A Combustion Evaluation Report

Dear Mr. Riley:

Ecology has received and reviewed the IWAG's April 24, 2017, *Zone A Combustion Evaluation Report – Pasco Sanitary Landfill* (combustion report). Ecology thanks the IWAG and its technical representatives for submitting the report, and for the work performed in accordance with the IWAG's October 2016 *Detailed Work Plan to Evaluate Potential Combustion in Zone A*. Ecology provided conditional approval to proceed with the combustion evaluation work in a letter dated November 7, 2016. This letter provides Ecology's formal response to the contents of the combustion report.

BACKGROUND

An earlier Zone A heating evaluation was conducted in 2012/2013 in response to various data and observations made after the Zone A soil vapor extraction (SVE) system was upgraded and activated. The potentially liable persons (PLPs) concluded in their memorandum of findings that the elevated temperatures and associated changes in subsurface gas composition beneath Zone A were due to *biologic* activity and not caused by subsurface oxidation (i.e., not a true subsurface combustion event). Around this same time (late 2013), a subsurface fire in the Balefill Area was identified near the northeast corner of Zone A. Ecology and PLP resources, by necessity, shifted to focusing on determining the nature and extent of the Balefill Area fire, and how to extinguish this municipal solid waste subsurface combustion event. The Zone A SVE system operations were modified to help limit the potential influence of active gas extraction on the Balefill Area fire, while seeking to capture contaminant mass from beneath Zone A.

The Balefill Area subsurface landfill fire response actions (Cement-Bentonite-Wall Box excavation, waste quenching, and installation of Soil-Cement-Bentonite [SCB] Barrier Wall) were conducted during late summer/fall of 2015. A follow-up phase of post-extinguishment fire monitoring (both temperature and subsurface soil/waste gas) extended into the winter of 2016. During this time, Ecology began to see evident changes in certain Zone A operations and monitoring data, and reconsidered these changes in conjunction with other associated Zone A observations, including:

- Significant, short-term changes in the gas composition (oxygen, carbon dioxide, and lower explosive limit) at selected Zone A extraction and vapor monitoring wells
- Elevated wellhead vapor temperatures at and above 140°F at selected Zone A SVE wells
- Elevated carbon monoxide (CO) concentrations in selected SVE wells — approaching 1,000 parts per million volume (ppmV)
- Continued evidence of progressive, ground/cap settlement from 2013 through 2015 in localized areas of Zone A resulting in closed depressions up to 6 feet deep

- Large soil cracks in several areas of the Zone A vegetative soil cover, extending down to the underlying geotextile (above the drainage layer) and possibly the high-density polyethlylene liner
- Excessive grout loss during SCB Barrier Wall installation and during previous Phase II Additional Interim Action horizontal drilling — the grout losses suggest the presence of substantial void space within selective Zone A waste zones — something not expected in well-compacted waste materials emplaced more than 40 years ago
- Documented evidence of charred waste encountered in previous Zone A borings (see for example boring log descriptions from MW-52S, MW-53S) and in materials retrieved from the SCB Barrier Wall excavation
- Vertical Zone A temperature profiles from July 2012 showing elevated subsurface temperatures approaching 150°F in selected Zone A wells
- Progressive increase in groundwater temperatures beneath Zone A by 10 to 12°F from 2011 through 2016 as compared to temperature conditions and trends observed in background wells positioned hydraulically upgradient of Zone A (e.g., MW-26S).

These various lines of evidence, considered together, supported Ecology's decision to require the PLPs to evaluate Zone A combustion. Subsurface combustion, if present beneath Zone A, creates an unacceptable threat to human health and/or the environment due to the types of wastes present, combustion byproducts created, and the potential impacts to site workers and nearby residents and businesses. While alternative explanations potentially could account for these various lines of evidence, Ecology believes a true smoldering combustion condition either (1) has occurred, (2) is occurring, and/or (3) likely could occur beneath Zone A. Based on Ecology's opinion that subsurface combustion was or is occurring, this condition cannot be treated as inconsequential and resolved by allowing the combustible materials to burn out or self-extinguish over time. The threat posed by a likely subsurface fire has already adversely impacted ongoing interim action remedial operations. The threat posed by a likely subsurface fire also has affected the focused feasibility study (FFS) process of identifying a preferred remedial alternative for the Zone A waste repository.

USE OF ALTERNATIVE COMBUSTION LINES OF EVIDENCE FOR 2017 COMBUSTION REPORT

Ecology believes that the current legal landscape at this cleanup site has been and continues to be adversely influenced by litigation between various PLP groups. This backdrop of litigation has affected the quality, content, and technical legitimacy of certain lines of evidence presented in the IWAG's combustion report. Ecology does not believe the document provides the most plausible and defensible explanation for the multiple lines of evidence under consideration.

The authors of the combustion report have omitted relevant, commonly applied landfill combustion indicators and assessment criteria (e.g., see Federal Emergency Management Agency [FEMA], 2002; Ohio Environmental Protection Agency [Ohio EPA], 2011; California Department of Resources Recycling and Recovery [CalRecycle], 2006). The combustion report excludes other essential and relevant lines of evidence that Ecology specifically identified in our November 7, 2016, Conditional Approval letter. The IWAG has claimed that certain lines of evidence (settlement, soot, voids, charring on waste debris) are either irrelevant, or are indicative of other non-combustion processes or mechanisms. This exclusion of other legitimate lines of evidence broadly recognized by other landfill combustion researchers and investigators further supports Ecology's decision to question the IWAG's analysis and interpretation of Zone A conditions in the combustion report.

The IWAG combustion report includes several assertions that ignore, attempt to override, or re-write well-established, internationally recognized fire indicators and indicator thresholds. Page 5 (Section 2.3) of the combustion report, for example, suggests there is extensive new landfill fire research conducted since the 2002 FEMA guidance was issued that provides a "new understanding of landfill combustion." A main goal of this discussion appears to include creating speculation about CO as a primary landfill fire indicator. In our review of the current knowledge regarding landfill fires, the presence of CO above 1,000 ppmV in landfill gas remains a primary indicator of subsurface combustion. Ecology believes the IWAG's assertions casting doubt on well-established landfill fire indicator thresholds offer no meaningful value to the current evaluation and analysis of actual, measurable, demonstrable processes occurring at Zone A.

Ecology notes that several broadly accepted thresholds and fire indicators presented in FEMA (2002), Ohio EPA (2011), CalRecycle (2006), and other recognized landfill fire sources have been used, referenced, and reported in previous IWAG-sponsored documentation. A few examples of these documents are highlighted below:

1. **October 2016 *Enforcement Order Task 2 Technical Memorandum* prepared by Anchor QEA on behalf of the IWAG:** Page 21, Section 3 of the memo identifies six qualitative and quantitative parameters used to confirm subsurface combustion. These six parameters are taken from the May 2002 FEMA guidance document titled *Landfill Fires — Their Magnitude, Characteristics and Mitigation*. The IWAG's inclusion of these combustion indicators demonstrates its overall endorsement of these parameters for combustion evaluation purposes.
2. **May 21, 2014, memorandum *Pasco Landfill: Balefill Area Combustion — Assessment of Causation* prepared by the IWAG Group III Technical Committee:** Page 3 of the memorandum refers to the Zone A Heating Evaluation, and the use of a 170°F temperature threshold as indicative of potential subsurface combustion. The memorandum references the 2002 FEMA guidance document as the basis for this indicator threshold. The memo also discusses on page 3 the use of soot in the SVE system as another subsurface combustion indicator.
3. **December 16, 2013, memorandum *Literature Review of Ignition/Combustion in Soil* prepared by GSI Environmental for Anchor QEA:** Page 2 of this memo, under the subsection titled Subsurface Landfill Fires, states that "[s]ubsurface landfill fires are 'more likely to burn slowly without visible flame or large quantities of smoke and are characterized by rapid oxidation of an organic waste' (CalRecycle, 2006). Two key characteristics of smoldering landfill fires is that they 'can propagate at oxygen concentrations below 3 percent (DeHann, 2007) and have been documented to persist with a solid waste landfill between 212F and 250F (Ettala et al., 1996)' (as reported by Thalhamer, 2013)." The 2013 GSI memorandum goes on to discuss autoignition temperatures on page 2, stating that "[i]f carbon disulfide is present in the subsurface, it is possible that the autoignition temperatures of the gas mixture within the Pasco Landfill is as low as 194°F. Trace components of carbon disulfide would be the first to ignite if these higher temperatures are reached and there is not mechanism for the heat to escape (Management and Prevention of Sub-surface Fires, 2008)." Ecology notes a 98 percent and 88 percent detection frequency for carbon disulfide in SVE vapor samples collected from wells VEW-06i and VEW-07i. Ecology notes that temperatures of 194°F and higher were reported in many of the Zone A Rotosonic boreholes drilled in January 2017. On page 3, under the subsection "Explosions in Porous Media," the GSI memorandum notes that "any flammable gases could contribute to the smoldering process of a subsurface fire."
4. **June 4, 2014, memorandum *Pasco Landfill – Balefill Area Interim Action Fire Suppression Work Plan* prepared by the IWAG Technical Committee in consultation with Anchor QEA, Environmental Partners Inc., and SCS Engineers:** Page 7 of the memorandum states that "CO in soil gas in several locations was above 1000 parts per million – Volume (ppmV), which is one indicator of possible subsurface combustion." Page 7 of this memo reiterates the use of a 170°F threshold as indicative of possible subsurface combustion. Page 8 of the memorandum discusses settlement monitoring of the Balefill Area Repair Area, demonstrating the IWAG's recognition of ground settlement as a possible combustion indicator. Page 11 of the memorandum makes reference to the 2002 FEMA guidance document on landfill fires, along with reference to a 2011 Ohio EPA document titled *Subsurface Heating Events at Solid Waste and Construction and*

Demolition Debris Landfills: Best Management Practices. Reference to these two well-recognized, authoritative landfill fire guidance documents indicates IWAG endorsement of their contents.

5. **January 11, 2016, letter – *Opinion Letter, Zone A, Pasco Sanitary Landfill, Pasco, Washington*, prepared by SCS Engineers:** The letter specifically references FEMA (2002) and Ohio EPA (2011) as authoritative landfill guidance documents, and lists six key indicators of a heating event related to subsurface combustion in landfills: (1) substantial settlement, (2) smoke or smoldering odor, (3) elevated CO >500 to 1,000 ppmV, (4) combustion residue in probes or wells, (5) gas temperature >140°F, and (6) subsurface soil temperatures >170°F. The SCS letter states that "these parameters are widely used as indicators of subsurface heating events relate to combustion."

One of the IWAG's consultants (SCS Engineers) also has generated landfill fire documentation related to work it performed on the Bridgeton Landfill subsurface fire in Bridgeton, Missouri. SCS Engineers prepared a September 9, 2015, document for Bridgeton Landfill, LLC titled *Evaluation of Remedial Action Approaches for Hot Spot Remediation*. Appendix D (Local Subsurface Oxidation (SSO – Potential Landfill Fires) of that document includes the following passages:

- "Subsurface Oxidation Events (SSO) are common events that occur at many landfills that have active gas collection systems. These are local subsurface fires that are caused by a combination of subsurface conditions and well management. Unlike large subsurface reactions (which are extremely rare, do not require oxygen to propagate, and are quite different in nature), SSOs usually only involve a small area and a minimal number of gas wells." *Appendix D, page 1.*
- "SSOs are often caused by "overpulling" a gas well or wells in a certain area. Oxygen is drawn into the waste mass which can generate heat and provide the necessary oxygen for combustion. . . ." *Appendix D, page* 2.
- "The key to stopping SSO once it has begun is to completely restrict oxygen from entering the smoldering waste mass (snuff out the fire). . . ." *Appendix D, page* 3.

The 2015 SCS Engineers document (Appendix D, page 1) goes on to describe typical symptoms of a subsurface oxidation event, including dramatic localized landfill settlement, drastic or unusual increase in flowing gas temperature, and abnormally high CO concentration in landfill gas. With respect to elevated CO, page 2 of Appendix D notes that "[g]as quality in wells adjacent to the SSO *may* be affected. In particular, carbon monoxide levels could elevate based on wellfield operations and preferred pathways within the waste mass." Ecology notes that the SCS report makes no attempt to suggest that biological processes are the source for the measured CO observed in the landfill wells.

Ecology highlights the above documents to emphasize that the IWAG and its consultants have affirmed the legitimacy and relevance of these industry-recognized indicator thresholds, criteria, and assessment approaches as they relate to subsurface landfill fires (aka subsurface oxidation events). The IWAG's use of the Pasco Landfill as a testing ground for application of unproven thresholds and indicators based on a "new understanding of landfill combustion" is inappropriate and lies outside of the assessment scope established for the Zone A combustion evaluation work.

IWAG DISPUTE OVER HAMMER CONSULTING SERVICES FIRE EXPERT ROLE

During the past few months, the IWAG also has sought to discredit and limit Mr. Todd Thalhamer's (Hammer Consulting Services) involvement as a landfill fire technical expert, supporting Ecology in its review of the IWAG combustion report. The IWAG's legal tactics highlight the degree to which non-relevant legal considerations tied to its litigation against the Landfill Group have impeded the goal of seeking a technically sound and objective analysis of Zone A subsurface conditions. The IWAG has claimed that Mr. Thalhamer has a serious conflict of interest, and that he has willfully and deliberately biased his expert opinions about the true nature of Zone A subsurface conditions based on a purported business relationship between himself and Mr. Tony Sperling (another industry-recognized landfill fire expert). Ecology believes this contention is erroneous and baseless.

APPARENT IWAG CSM TO EXPLAIN RECENT PAST AND PRESENT ZONE A CONDITIONS

Ecology has attempted to understand and reconstruct the technical underpinnings and operative conceptual site model (CSM) that the IWAG has developed to support and defend the arguments and conclusions presented in the combustion report. Table 1 (enclosed) presents Ecology's attempt to capture a number of core, fundamental, assumptions and CSM components as gleaned from the combustion report, other Zone A combustion-related literature prepared by the IWAG, and ongoing communications and information exchange.

Ecology believes the Table 1 compilation of operative technical assumptions and arguments developed and used by the IWAG's technical experts readily exposes the incomplete and seemingly biased technical foundation upon which these arguments have been developed.

COMPARISON OF IWAG AND ECOLOGY COMBUSTION EVALUATION METRICS

Ecology believes submitting comments to address specific elements of the combustion report would be an ineffective use of time and resources in view of our assessment of that report's content and technical foundation. The objective of evaluating Zone A combustion, as described in the December 9, 2016, *Second Revised Work Plan to Evaluate Potential Combustion in Zone A*, 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." The combustion report did not produce a conclusive body of evidence indicating, with any degree of confidence that combustion has not, is not, or will not occur within Zone A. Therefore, Ecology is rejecting the conclusions within the combustion report. Table 2 (enclosed) provides a comparative analysis of IWAG and Ecology combustion evaluation metrics. This table provides the technical basis supporting Ecology's decision to reject the report's content, analysis, and conclusions.

ECOLOGY DETERMINATION ABOUT ZONE A COMBUSTION CONDITIONS

Ecology has independently reviewed the combustion report; its decision to reject the conclusions is based on the opinions of Ecology's technical leads (Messrs. Gruenenfelder, Schmidt, and Fees/Ecology TCP-ERO). Ecology also hired a well-recognized landfill fire expert (Mr. Todd Thalhamer) to perform his own independent review and analysis of the combustion report. Mr. Thalhamer performed his review under a collaborative work arrangement with Hart Crowser, an Ecology prime contractor. Mr. Thalhamer's review comments and evaluation of the IWAG combustion report are included in a memorandum enclosed with this letter.

Ecology and Mr. Thalhamer have determined that a subsurface landfill fire likely has, is, and/or very likely will occur beneath Zone A. This shared perspective is based on a full consideration of relevant and commonly accepted lines of evidence, subsurface fire indicators, and threshold criteria used to evaluate potential subsurface landfill fires.

In addition to the conclusion that a subsurface fire likely has, is, and/or will occur, Ecology has additional concerns that recent measurements of flammable liquids [i.e., non-aqueous-phase liquid (NAPL)] accumulated in the subsurface beneath Zone A also may pose an additional threat to human health and the environment. A discrete pocket of NAPL was found within soil/waste debris at depths of approximately 30 to 35 feet below grade during the January 2017 subsurface investigation work at Zone A. A layer of NAPL also has been discovered on top of groundwater in one Zone A monitoring well (MW-52S). A NAPL sample collected from monitoring well MW-52S in June 2017 showed a flash point of 85°F and a specific gravity of 1.02 grams per milliliter. For a flash point of 85°F, the Zone A NAPL designates as:

- *Flammable Liquid* – Occupational Safety and Health Administration (OSHA)
- *Flammable Liquid* – American National Standards Institute (ANSI)
- *Ignitable Liquid* – Resource Conservation & Recovery Act (RCRA)
- *Flammable Liquid* – Department of Transportation (DOT)
- *Category 3 Flammable Liquid and Vapor* – Globally Harmonized System (GHS)
- *Class 1C Flammable Liquid* – National Fire Protection Association (NFPA)

The potential consequences from combustion of this NAPL, which includes numerous chorinated solvents with the potential to form toxic gases such as phosgene and other toxic combustion byproducts, are not trivial and also need to be addressed. In addition, the density characteristics of this NAPL introduce possible concerns about its vertical migration into deeper portions of the aquifer system beneath Zone A.

STEPS AHEAD

Ecology is not asking the PLPs to revise the April 2017 combustion report. Instead, Ecology is prepared to engage with the IWAG and broader group of PLPs to determine what appropriate steps must be taken to proactively address conditions occurring beneath Zone A. A series of actions that Ecology expects the PLPs to pursue in response to this letter are summarized below.

FFS Report: On August 31, 2017, Ecology received revised FFS reports from the PLPs. The IWAG's position about Zone A combustion is openly evident by the content of the combustion report. At the time of this letter's submittal, Ecology had completed only a preliminary review of the revised FFS reports. Having received no communication from the IWAG signaling a change in their position about Zone A combustion conditions since the combustion report was submitted, Ecology will assume the revised FFS report retains much of it previous discussion of Zone A conditions. If Ecology's assumption is correct, it appears unlikely the revised FFS will include remedial alternative modifications that specifically address a Zone A combustion event.

Ecology has no plans to make allowances for another FFS report revision. The revised FFS report received on August 31, 2017, will be distributed for public review. Ecology will identify and document, as necessary, any portions of the FFS report where significant differences of opinion may exist. This could include, but may not be limited to, the IWAG's discussion of existing Zone A subsurface conditions and its preferred remedial action option.

Public Outreach and Participation: The current status of Zone A conditions (i.e., likely subsurface smoldering combustion and NAPL on groundwater) has not yet been actively communicated to the public. We have, however, updated our Pasco Landfill web page to include information about the potential subsurface smoldering combustion, the IWAG's investigation and resulting report, and the presence of NAPL on groundwater. In response to the FFS submission and our rejection of the findings in the combustion report, Ecology will initiate public outreach with the locally affected community. This will include informing them of current site conditions, potential risks, and possible response actions that likely will be taken over the months to come. Ecology invites the IWAG and other PLP groups to work collaboratively with us as we formulate and execute public outreach steps and activities, consistent with Chapters 173-340-120(9), -130(4), -400(3), -430(6), and -600 Washington Administrative Code.

Zone A Supplemental Monitoring: Ecology will require the PLPs to develop a plan (or plans) for supplemental subsurface monitoring at Zone A. Expedited, supplemental monitoring is needed to document current conditions and possible changes that may be occurring within and beneath Zone A. Conditions to be monitored include:

- Subsurface smoldering combustion
- Localized and distributed Zone A cap settlement

- NAPL composition and distribution on the water table beneath Zone A
- Permit-compliant interim action (IA) SVE operations
- Local groundwater quality conditions beneath, and immediately downgradient of, Zone A

Ecology recognizes that some of this monitoring is already in place, and some elements are under discussion. Ecology looks forward to working collaboratively with the IWAG and other PLP groups to develop an appropriate supplemental monitoring strategy for Zone A that can address all these various and overlapping conditions and IA monitoring obligations.

Meeting between Ecology Representatives and PLPs: Current Zone A conditions require an expedited response to minimize the potential for further adverse environmental impacts and to ensure that human health is adequately protected. In response to this letter, Ecology and our Assistant Attorney General on this project (John Level) will arrange a meeting with the Pasco Landfill PLPs to discuss the anticipated steps ahead to address the challenges posed by Zone A, and anticipated actions to address the consequences of subsurface smoldering combustion and NAPL releases.

In closing, Ecology and the IWAG appear to have reached very different conclusions about whether a smoldering combustion event likely has, is, and/or likely will occur beneath Zone A. However, Ecology is confident in its position, and believes the technical evidence demonstrating a past, present, and/or likely near-future subsurface smoldering combustion event is strong and indisputable. Based on this, Ecology is prepared to move forward with the FFS and prepare a draft Cleanup Action Plan (dCAP).

Current Zone A conditions pose an unacceptable risk to human health and the environment, and as such the consequences of a release of flammable liquids from the inventory of hazardous waste buried in Zone A must be addressed. Ecology prefers to work cooperatively with the PLPs to develop IA remedial responses that will aggressively and permanently mitigate these threats. Toward that end, Ecology expects the IWAG and broader group of PLPs to pool their talents and technical resources and develop an appropriate long-term solution for Zone A that minimizes further cleanup delays, limits legal maneuvering, and avoids unnecessary expenditures on ineffective outcomes.

Ecology anticipates further discussion of this letter, its conclusions and expectations, and steps ahead with the broader group of PLPs during our upcoming Ecology/all-PLP meeting on September 19, 2017. We trust these discussions will help determine the preferred path the parties plan take to address these existing Zone A conditions, and lay the groundwork for collaborative interactions that will carry us through the FFS and dCAP process.

Sincerely,

Chuck Gruenenfelder

Chuck Gruenenfelder
Project Manager
Toxics Cleanup Program

CG:jab

Enclosures

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Table 1. Summary of Apparent Zone A Conceptual Site Model and Smoldering Combustion Assumptions

Zone A Cap Settlement	Zone A cap settlement is caused exclusively by drum release and associated drum collapse in response to normal overburden pressure of the overlying soil and landfill cap materials.
Smoke as a Primary Combustion Indicator	The lack of smoke emanating from Zone A wells and boreholes demonstrates a lack of subsurface smoldering combustion. Active operation of the SVE system and maintenance of a negative pressure within the Zone A subsurface apparently does not affect this observation.
Elevated Carbon Monoxide Levels	Elevated CO levels are produced "as a result of biological degradation of the waste under limited oxygen conditions" (see page 6 of the combustion report). These natural biodegradation processes can produce CO concentrations >1000 ppmV for an extended period of time. Elevated subsurface temperatures do not impact the survival of a unique class of thermophilic bacteria that mediate this process.
Heat Produced by Composting/Biodegradation	A unique class of thermophilic bacteria is responsible for generating the elevated CO levels and associated heat through biodegradation. These unique anaerobic thermophiles do not produce significant quantities of methane or hydrogen sulfide.
In-situ Subsurface Soil Temperatures	Soil core temperatures greater than 170°F are caused solely by frictional heat associated with the Rotosonic drilling, and are not indicative of actual in-situ soil/waste-mass temperatures created by other subsurface processes.
Homogeneous Mixed Debris Temperatures	Nearly isostatic vapor and waste mass temperatures are being maintained within the discontinuous, heterogeneous waste materials beneath Zone A. The 150°F+ vapor temperatures are created and sustained by thermophilic bacteria thriving at depth beneath Zone A, without the need for a large, continuous body of biodegradable waste debris.
Sustained Subsurface Vapor Temperatures	Sustained subsurface vapor temperatures up to and above 140°F are caused by the biodegradation of the waste materials by a unique class of thermophilic bacteria. These elevated temperatures have been sustained for a 5-plus-year time period — despite limited TVS and relatively dry subsurface conditions where bacteria normally do not thrive.
Soot as a Combustion Indicator	Chemical analysis of possible combustion residues (i.e., soot and associated combustion byproducts) within existing SVE wells is not a useful combustion indicator for the 2017 combustion report, despite its inclusion in the 2012 Zone A Heating Evaluation.
Biodegradation of Hazardous Wastes	A unique class of thermophilic bacteria have successfully maintained subsurface vapor temperatures between 148 and 151°F during the past six months (January through July 2017) — over 5 years after the upgraded SVE system became operational. This heat-liberating biological activity involves active biodegradation of the drummed hazardous wastes, since a continuous mixed debris layer reportedly does not exist, TVS and carbonaceous content of the remaining waste

Table 1. Summary of Apparent Zone A CSM and Smoldering Combustion Assumptions (continued)

	material is low, and calculated CO_2/O_2 ratios indicate little mixed MSW debris is even present.
Unique Subsurface Biome	A substantial quantity of biologically active waste substrate would normally be required to generate the large quantities of heat observed in the Zone A subsurface via biodegradation. The Zone A bacterial community, however, is specialized and uniquely capable of targeting and biodegrading the toxic, Zone A hazardous wastes. Biome studies or microbial assays demonstrating this assumed biodegradation mechanism are not necessary to support the core hypotheses about Zone A subsurface conditions.
Aerobic vs. Anaerobic Conditions	Despite active SVE operations and the significant movement of air within the vadose zone, the subsurface biological community beneath Zone A is robust enough and distributed broadly enough to create and sustain largely anaerobic conditions throughout large portions of Zone A. These anaerobic bacteria can survive and thrive in a relatively dry, low TVS, chemically hostile environment, and do not generate a significant quantity of methane or hydrogen sulfide.
Lateral Continuity of Zone A Waste Material	Potentially combustible Zone A waste materials are not laterally continuous, thereby limiting the potential for a possible subsurface combustion event.
TVS Content of Zone A Waste Material	The TVS content of the remaining Zone A waste material is too low to allow a sustainable combustion reaction to occur within the sparsely distributed pockets of Zone A waste.
Origin of Zone A Charred Debris	Any charred debris encountered in previous or recent Zone A boreholes is singularly representative of combustion residuals from burn trench waste disposal operations that occurred prior to 1972 (see, for example, the November 23, 2016 Anchor QEA email).
Thermocouple Design and Construction	Construction characteristics of the Zone A thermocouples have no effect on their ability to record representative in-situ waste/soil temperatures. Silica sand used as a sand pack around the thermocouples and the open, air-filled PVC piping to which the thermocouples are attached exert a negligible influence on subsurface heat transfer processes and the temperatures recorded by the thermocouples.
Basis for Thermocouple Temperature Fluctuations	Synchronous subsurface temperature fluctuations observed in spatially separate boreholes (and in vertically separated thermocouples located within the same borehole) can be traced to equipment malfunction and are not a reflection of actual subsurface conditions.
Basis for Remnant Voids in Zone A Wastes	Large void spaces encountered beneath Zone A can all be attributed to poor landfill compaction processes, disposal of large objects, and/or MSW biodegradation (see November 23, 2016 Anchor QEA email). The overburden pressure that causes the leaking drums to collapse (see Zone A Cap Settlement above) does not induce collapse of these other subsurface voids.
SVE Operational Factors and Subsurface Oxidation Events	Operational conditions that potentially can cause a subsurface oxidation event [see 2015 SCS Engineers report *Evaluation of*

Table 1. Summary of Apparent Zone A CSM and Smoldering Combustion Assumptions (continued)

	Remedial Action Approaches for Hot Spot Remediation (Bridgeton Landfill Fire)] do not apply to the Zone A SVE system operations.
Oxygen Levels to Sustain Smoldering	The minimum oxygen requirements to sustain a smoldering landfill fire have undergone a recent re-evaluation. The December 16, 2013 memorandum prepared by GSI Environmental for Anchor QEA notes that smoldering landfill fires can propagate at oxygen concentrations <3% (with reference to DeHann, 2007). In contrast, the 2017 combustion report states that oxygen concentrations <3% cannot support smoldering combustion (with reference to U.S. Navy, 1998).

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MSW – municipal solid waste
O_2 – oxygen
ppmV – parts per million volume
PVC – polyvinyl chloride
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TVS – total volatile solids

Table 2. Comparative Analysis of IWAG and Ecology Combustion Evaluation Metrics

Combustion Evaluation Metric	IWAG Observation	IWAG Rationale	IWAG Conclusion	Ecology Observation	Ecology Rationale	Ecology Conclusion
Visual Observation of Smoke	Smoke and embers have not been observed in Zone A.	Smoke is a confirmatory indicator of subsurface combustion. (Note that steam is indicated instead of smoke if the ambient temperature is conducive for steam generation and the cloud dissipates quickly).	A positive detection of smoke is the most definitive indicator of combustion, so the lack of it does not support combustion.	Smoke is not a singular, confirmatory indicator of subsurface combustion. Operation of an SVE system and maintenance of a negative pressure within the waste zone interior would minimize the likely observation of smoke from any Zone A borehole or soil/waste debris. The IWAG rationale is inconsistent with prevailing industry understanding of subsurface combustion mechanisms.	Page 2 of a December 16, 2013 Memorandum *Literature Review of Ignition/Combustion in Soil* prepared by GSI Environmental for Anchor QEA states that "[s]ubsurface landfill fires are 'more likely to burn slowly without visible flame or large quantities of smoke and are characterized by rapid oxidation of an organic waste' (CalRecycle, 2006)." Ohio EPA (2011) notes that "the absence of smoke is not confirmation that a subsurface heating event is not occurring. The disposed material can filter the visible particulate matter from the smoke." Foss-Smith (2010) notes that "visible smoke might not be visible since compacted waste acts as a good particulate filter." Similarly, other investigators have noted that underground borings frequently do not encounter the heart of a landfill fire where the highest temperatures are present and the material is actually undergoing active combustion.	The lack of smoke or embers in drilled boreholes, and/or a lack of smoke emanating to the surface of the capped landfill via fugitive emissions through conduits in the Zone A geomembrane (i.e., tears, poorly sealed boots, etc.) is not a definitive line of evidence to exclude the possibility of a subsurface smoldering combustion event.

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Table 2. Comparative Analysis of IWAG and Ecology Combustion Evaluation Metrics (continued)

Combustion Evaluation Metric	IWAG Observation	IWAG Rationale	IWAG Conclusion	Ecology Observation	Ecology Rationale	Ecology Conclusion
In-situ Soil Temperatures	Maximum in-situ temperatures recorded were 159°F during the main testing period.	The 2002 FEMA landfill fire guidance 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.	In-situ temperatures are within range of heat-generating biological processes (up to 176°F, Jafari et al., 2017) and far below the range expected for initiation of spontaneous combustion (>~392°F) (Moqbel et al., 2010). In-situ temperatures do not support combustion.	Temperature data from Zone A thermocouples showed temperatures up to (and likely above) 165°F. Many thermocouples were installed in subsurface horizons containing little observable carbonaceous waste material. Soil cores retrieved from Zone A drilled boreholes showed temperatures exceeding 200°F in several locations. The IWAG has argued that heat generation from the Rotosonic drilling method can fully account for all subsurface soil core temperatures >170°F. The prevailing IWAG hypothesis is that thermophilic bacteria exist beneath Zone A and are surviving at temperatures up to and exceeding 165°F. The confirmed presence of thermophilic extremophiles (i.e., bacteria potentially capable of surviving at temperatures >165°F) has not been documented at this site.	The IWAG argued that temperature data from the TC2-16 thermocouple were inaccurate due to the use of incorrect extensions. The data from TC2-27 showed a similar temperature response pattern to the observations at TC2-16. In addition, the temperature response patterns at a spatially distant thermocouple installed in a separate vertical array (TC4-19) simultaneously mimicked the temperature fluctuation pattern observed at TC2-16. These synchronous temperature response patterns at vertically separated monitoring stations (TC2-16 and TC2-27) and horizontally separated monitoring stations (TC2-16 and TC4-19) demonstrate that all three thermocouples were recording a similar temperature event simultaneously. IWAG efforts to selectively exclude temperature data from TC2-16 would not appear defensible. The IWAG also selectively excluded discussion and presentation of the soil boring temperature data, including borings with subsurface temperatures >170°F. Large temperature gradients of 80 to 100°F observed over short vertical distances in the Rotosonic boreholes cannot be attributed singularly to drilling method influences. The thermocouple construction method also raises questions about the representativeness of the temperature readings obtained (i.e., recorded thermocouple temperatures may low-bias the actual in-situ soil/waste mass temperatures beneath Zone A).	In-situ soil temperatures at and above 170°F are present beneath Zone A. This is demonstrated by soil boring cores and existing thermocouple data. This evidence is indicative of subsurface smoldering combustion event.

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Table 2. Comparative Analysis of IWAG and Ecology Combustion Evaluation Metrics (continued)

Combustion Evaluation Metric	IWAG Observation	IWAG Rationale	IWAG Conclusion	Ecology Observation	Ecology Rationale	Ecology Conclusion
CO Concentrations	• 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.	The 2002 FEMA landfill fire guidance uses CO as a general confirmatory indicator of combustion. CO is produced at landfills by non-combustion sources as well.	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. Potential combustion cannot be not confirmed [sic] by this indicator alone.	CO concentrations >1000 ppmV have been documented in samples collected from Zone A SVE wells and gas probes. 1000 ppmV is a common, internationally used combustion-indicator threshold.	Elevated CO concentrations >200 ppmV have been noted beneath Zone A since 2012. Laboratory analysis of Zone A gas and vapor samples from SVE wells and gas probes during 2016 and 2017 identified CO concentrations up to 1400 ppmV. The IWAG's attempts to suggest that 1400 ppmV CO is due to biological processes, whereas 1500 ppmV CO would be more indicative of a combustion-derived origin, is non-defensible, particularly in an environment subject to substantial vapor migration from ongoing SVE operations. The sustained presence of CO at concentrations at or above 1000 ppmV in multiple gas/vapor samples over the past year is a broadly-accepted combustion line of evidence. Statistical analysis using the existing distribution of CO results demonstrates CO concentrations at and above 1500 ppmV likely would exist based on a prediction limit approach. The IWAG's 2012 Zone A Heating Evaluation attempted to explain elevated CO as the result of bacterial oxidation of methane, concluding that observed CO levels were in the range of landfill CO generation under *aerobic* conditions. In contrast, the IWAG's 2017 combustion report now concludes that "an increase in CO from non-combustion biological processes is expected when an aerobic system is converted to a deeply anaerobic system …" The obvious contradiction between these two statements exacerbates Ecology's concern over the IWAG's analysis in the 2017 combustion report.	Observed CO measurements from SVE wells and gas probes support the likelihood for a subsurface smoldering combustion event.

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Table 2. Comparative Analysis of IWAG and Ecology Combustion Evaluation Metrics (continued)

Combustion Evaluation Metric	IWAG Observation	IWAG Rationale	IWAG Conclusion	Ecology Observation	Ecology Rationale	Ecology Conclusion
CO_2/O_2 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 MSW-like material).	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.	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. This metric does not support combustion.	The IWAG's analysis isolates a limited set of data from selected monitoring stations and applies unsupported claims and conclusions about the apparent origin for the observed CO_2/O_2 in the Zone A subsurface. The technical approach used to defend this apparent combustion metric is difficult to follow. The analysis appears to hinge on the use of standard combustion/biodegradation regression lines for which no reference to any literature source is provided. The authors openly acknowledge that "this method does have some uncertainty and should be given less weight than other combustion metrics …"	This combustion evaluation metric is insufficient as an acceptable line of evidence. Chlorinated compounds are completely ignored in the IWAG's analysis. The authors are contradictory over which conditions – aerobic or anaerobic – actually exist beneath Zone A. Methane is produced via anaerobic processes and is called out as a key, representative compound that, along with toluene and 2-butanone reportedly undergoes aerobic biodegradation, and produces a distinguishable CO_2/O_2 gas signature.	The attempted use of a CO_2/O_2 relationship to speculate that no subsurface smoldering combustion could have, or could be occurring is technically non-defensible.
Characteristics of Mixed Debris Layer	The mixed debris was generally encountered in separate lenses 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 5 feet apart.	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. The degree of continuity of the mixed debris observed in Zone A is also a critical factor in assessing the potential for combustion.	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. This metric does not support combustion.	The need for a continuous waste zone to support combustion beneath Zone A is unnecessary. Numerous Zone A boreholes encountered either not combusted, partially combusted, or wholly combusted materials (i.e., ash or metallic residue). Elevated temperatures have existed beneath Zone A since at least 2011, and generation and maintenance of this heat flux would require either composting/biodegrading or combusting. Therefore, a sizable quantity of potentially combustible material has likely already been consumed. The Zone A combustion evaluation should have considered if combustion either has occurred, is occurring, or will occur.	The existing distribution of potentially combustible waste materials beneath Zone A offers an insufficient basis for drawing any scientifically based conclusions about the potential for a combustion event to initiate, spread, and remain sustained for an extended time period. The IWAG's conclusions about the apparent quantity, distribution and lateral continuity of bulk waste beneath Zone A, and their assumptions as to what quantity or concentration of waste material is necessary to support subsurface combustion (based on information from a handful of boreholes) are not technically defensible. The discussion excludes any mention of likely changes to the waste mass that likely has occurred over time. Ecology also notes this metric is not referenced as a recognized combustion indicator in any landfill fire guidance documents.	Evidence: The IWAG's analysis of carbonaceous content and the apparent lateral continuity of a mixed debris layer beneath Zone A is not an acceptable line of evidence to discount a potential smoldering combustion event beneath Zone A.

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Table 2. Comparative Analysis of IWAG and Ecology Combustion Evaluation Metrics (continued)

Combustion Evaluation Metric	IWAG Observation	IWAG Rationale	IWAG Conclusion	Ecology Observation	Ecology Rationale	Ecology Conclusion
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.	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.	Low levels of combustion material in the Zone A mixed debris make combustion unlikely, so this metric does not support combustion.	Elevated temperatures have existed beneath Zone A since at least 2011, and generation and maintenance of this heat flux would require either composting/biodegradation or combustion. Therefore, a sizable quantity of potentially combustible material has likely already been consumed. The Zone A combustion evaluation should have considered if combustion either has occurred, is occurring, or will occur.	Similar to the IWAG's attempts to use mixed debris continuity and mass distribution as a technically robust line of evidence to confirm/refute the likelihood for a subsurface combustion event, the TVS analysis presents similar technical shortcomings. Attempts at using contemporary Zone A waste TVS content from a limited number of soil boring samples as a valid combustion evaluation metric demonstrates a lack of understanding about historical waste distribution beneath the repository. Combustion beneath Zone A may have been triggered, via spontaneous combustion, within carbonaceous landfill waste. Reliance on subjective conclusions about the quantity and distribution of bulk waste and its corresponding TVS content is not considered a defensible combustion evaluation metric. Ecology also notes this metric is not referenced as a recognized combustion indicator in any landfill fire guidance documents.	The IWAG's analysis of TVS content of the mixed debris layer beneath Zone A is not an acceptable line of evidence to discount a potential smoldering combustion event beneath Zone A.

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Table 2. Comparative Analysis of IWAG and Ecology Combustion Evaluation Metrics (continued)

Combustion Evaluation Metric	IWAG Observation	IWAG Rationale	IWAG Conclusion	Ecology Observation	Ecology Rationale	Ecology Conclusion
Gas Autoignition Temperature	Test will be performed.	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.	No results yet (sample results not available as of 8/15/17).	Soil temperatures collected by the IWAG exceed 170°F, a commonly accepted indicator temperature threshold. Above 170°F, biological activity ceases within the interior of a landfill environment. No documentation has been generated by the IWAG to confirm that thermophilic extremophiles (i.e., bacteria potentially capable of surviving at temperatures >170°F) are present beneath Zone A. Temperatures at or above this 170°F threshold are indicative of active subsurface combustion.	Autoignition temperatures are most significant at the micro-scale where exothermic oxidation reactions can occur. These reactions can cause elevated temperatures within small, isolated portions of the waste mass. Spontaneous combustion can occur at this scale, depending on the nature of the waste materials or accumulated gases/liquids that may be present nearby. The December 16, 2013 Memorandum *Literature Review of Ignition/Combustion in Soil* prepared by GSI Environmental for Anchor QEA discusses autoignition temperatures, stating (page 2) that "[i]f carbon disulfide is present in the subsurface, it is possible that the autoignition temperatures of the gas mixture within the Pasco Landfill is as low as 194°F. Trace components of carbon disulfide would be the first to ignite if these higher temperatures are reached and there is not a mechanism for the heat to escape (Management and Prevention of Sub-surface Fires, 2008)." Ecology notes a 98% and 88% detection frequency for carbon disulfide in SVE vapor samples collected from wells VEW-06i and VEW-07i. Ecology notes that temperatures of 194°F and higher were reported in many of the Zone A Rotosonic boreholes drilled in January 2017. On page 3, under the subsection "Explosions in Porous Media," the December 2013 GSI memorandum notes that "any flammable gases could contribute to the smoldering process of a subsurface fire."	The IWAG still has not provided autoignition data — four months after submittal of its draft report. Ecology discounts the technical merits of this evaluation metric.

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Table 2. Comparative Analysis of IWAG and Ecology Combustion Evaluation Metrics (continued)

Combustion Evaluation Metric	IWAG Observation	IWAG Rationale	IWAG Conclusion	Ecology Observation	Ecology Rationale	Ecology Conclusion
Significant Short-term Changes in Gas Composition	Not addressed by the IWAG as a combustion line of evidence.	Not addressed by the IWAG as a combustion line of evidence.	Not addressed by the IWAG as a combustion line of evidence.	Review of the routine gas monitoring data collected from Zone A extraction and monitoring wells demonstrates that significant short-term changes in gas composition (O_2, CO_2, %LEL) have been observed.	Well-accepted landfill fire guidance documents recognize significant short-term changes in subsurface gas composition as an important combustion indicator. In preparing its *Evaluation of Possible Impacts of a Potential Subsurface Smoldering Event on the Record of Decision – Selected Remedy for Operable Unit-1 at the West Lake Landfill* [adjacent to the Bridgeton Landfill], the U.S. EPA notes rapid or localized changes in landfill gas quality as an important indicator of a subsurface smoldering event. Foss-Smith (2010) also describes unexpected changes in landfill gas analysis both in concentration and relative proportions as a potential evidence of subsurface smoldering combustion.	Review of current and historical landfill gas monitoring data from Zone A shows evidence of significant short-term concentration changes for selected monitoring parameters. These changes provide another line of evidence indicating the likelihood of a subsurface smoldering combustion event.
Elevated Zone A SVE Wellhead Vapor Temperatures	Not addressed by the IWAG as a combustion line of evidence.	Not addressed by the IWAG as a combustion line of evidence.	Not addressed by the IWAG as a combustion line of evidence.	Zone A SVE wellhead vapor temperatures up to 151°F have been recently documented at VEW-07i. As a local basis of comparisôn, maximum vapor temperatures at the Pasco Landfill MSW Landfill central interior extraction wells (EW-20 through EW-24) measured between 2015 and the present range between 78 to 90°F.	Several well-accepted landfill fire guidance documents and literature sources (FEMA, 2002; Ohio EPA, 2011; CalRecycle, 2006) reference a vapor temperature value of 140°F as an important indicator of a potential smoldering combustion event. From a thermodynamic and heat-transfer perspective, subsurface waste mass temperatures in the Zone A subsurface must include temperatures well above 151°F to create a measured vapor temperature of 151°F.	Elevated SVE wellhead and downhole vapor temperatures are a well-accepted line of evidence indicating the likelihood of a subsurface smoldering combustion event.
Settlement of Zone A Cap	Not addressed by the IWAG as a combustion line of evidence.	All documented Zone A cap settlement is caused by SVE system mass removal and subsequent drum collapse.	This metric is not a legitimate combustion line of evidence.	A significant magnitude of localized cap settlement has occurred, exceeding 6 feet in some locations. Broadly-distributed, lower-magnitude settlement also is observed throughout the entirety of Zone A.	SCS Engineers (2015) identifies "dramatic localized landfill settlement" as a typical symptom of a localized subsurface oxidation events. The IWAG notes that "[c]ap settlement … increased markedly but briefly from 2012 to 2014, and the rate of settlement has substantially decreased since 2014." FEMA (2002) lists substantial settlement over a short period of time as a primary indicator of a subsurface landfill fire.	Existing and historical occurrences of localized and areally distributed settlement supports the likelihood of a subsurface smoldering combustion event.

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Combustion Evaluation Metric	IWAG Observation	IWAG Rationale	IWAG Conclusion	Ecology Observation	Ecology Rationale	Ecology Conclusion
Large Soil Cracks in Zone A Cap – Vegetative Cover	Not addressed by the IWAG as a combustion line of evidence.	All documented Zone A cap settlement and associated cracking of the vegetative cover is caused by SVE system mass removal and subsequent drum collapse.	Not addressed by the IWAG as a combustion line of evidence.	Large, tensional soil cracks are observed around the localized Zone A cap settlement depressions, and in other locations on the Zone A cap. Ecology has field-verified that these cracks can extend down 3–4' below ground surface. Without any specific, field-verified evidence, the IWAG states in an 11/23/16 email message that observed soil cracks around the areas of settlement "do not penetrate or compromise the geomembrane cover of Zone A."	Patrick Foss-Smith, in a January 8, 2010 article in *Waste Management World* titled "Understanding Landfill Fires" states that "a confined fire might be indicated by a shallow collapse, surrounded by tension cracks, at the surface." SCS Engineers (2015) identifies "charred or cracked surface cover" as a typical symptom of a localized subsurface oxidation event. Disparate water accumulation observations within the two deepest Zone A settlement depressions raise questions about the integrity of the Zone A geomembrane.	The large area of differential settlement, along with corresponding deep soil cracks, support the likelihood that these features were caused primarily by a subsurface smoldering combustion event.
Charred Waste Materials	Not addressed by the IWAG as a combustion line of evidence.	Charred waste materials encountered in borehole samples are singularly attributable to prior (pre-1972) burn pit operations.	Not addressed by the IWAG as a combustion line of evidence.	Charred debris was identified in several Zone A boreholes during the 2017 Zone A Combustion Evaluation. For example, a strong, burnt tire-like odor and considerable charred material was evident to Ecology personnel who observed drilling at borehole BA-5. In addition to charred debris, zones of ash-like material (logged as "silt" by the IWAG's field representative) also was observed in various boreholes. Charred debris also was evident in previously drilled Zone A boreholes such as MW-52S and MW-53S. These observations cannot be singularly attributed to historical burn pit/burn trench operations.	Charring is a definitive indicator of combustion. The presence of charred material within the Zone A wastes retrieved during the drilling campaign indicates the likelihood of past or ongoing combustion beneath Zone A. Historical burn trench/burn pit materials also could be present, but given the time elapsed since disposal and subsurface processes expected to occur over this period, these materials would not show "fresh" indications of recent combustion activity.	Charred materials encountered in several boreholes indicate the likelihood of past or ongoing smoldering combustion activity beneath Zone A. Visual and olfactory observations at borehole BA-5 provide a high likelihood that mixed wastes, including tire materials, were actively experiencing combustion, or had recently undergone combustion.
Soot and Residue within SVE Wells	Not addressed by the IWAG as a combustion line of evidence.	Residues and encrustations observed in several SVE wells are entirely due to biological processes.	Not addressed by the IWAG as a combustion line of evidence.	Recent downhole video inspections of Zone A SVE wells show the presence of considerable residue and encrustation within both deep SVE wells and one intermediate well. The residue material is present throughout most of the wellbore interior of the deep wells. The residue appears dark and soot-like over some intervals.	No chemical analysis of the wellbore interior residue material has been performed recently. The appearance of the residue material suggests potential combustion-related soot or combustion by-product materials may be present. This potential line of evidence would be a definitive indicator of a combustion event if sooty particulates and/or combustion byproducts (PAHs, dioxins/dibenzofurans) were present in the residue materials.	Ecology may require analytical testing of SVE well residues for the presence of soot and soot-related compounds to provide another line of evidence to support the Zone A Combustion Evaluation.

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Combustion Evaluation Metric	IWAG Observation	IWAG Rationale	IWAG Conclusion	Ecology Observation	Ecology Rationale	Ecology Conclusion
Large Subsurface Voids beneath Zone A	Not addressed by the IWAG as a combustion line of evidence.	Large voids encountered within the Zone A subsurface are due to "poor landfill compaction practices, disposal of large objects and/or biodegradation of MSW" (11/23/16 IWAG email).	Not addressed by the IWAG as a combustion line of evidence.	Large voids have been identified beneath Zone A during three separate drilling and construction campaigns: Phase II AIA horizontal boring evaluation; SCB Barrier Wall construction; 2017 Zone A Combustion Evaluation drilling campaign. These large voids would not be expected at depths of 20 to 30 feet bgs (or more) in a 40-year-old waste repository that had undergone significant compaction during soil cap preparation and associated overburden pressure caused by the soil cover materials.	The presence of large voids further reinforces the likelihood that subsurface combustion processes have occurred beneath Zone A. The observed settlement of the Zone A cap, in combination with large residual voids, is not readily explainable using the IWAG's hypothesis about collapsing drums as the liquid contents leak out. The IWAG's other purported explanations (poor compaction, disposal of large objects, MSW biodegradation) are not supported by site conditions.	Large voids beneath Zone A provide additional evidence of subsurface processes that were capable of removing a sizable mass and volume of waste debris. This line of evidence supports the likelihood that combustion activities have occurred beneath Zone A.
Sustained, Elevated Groundwater Temperatures beneath Zone A	Not addressed by the IWAG as a combustion line of evidence.	No IWAG explanation has been provided to account for the significant heat flux and heat transfer that causes groundwater temperatures beneath Zone A to remain as much as 13 to 14°F higher than background temperatures.	Not addressed by the IWAG as a combustion line of evidence.	Groundwater temperatures beneath Zone A are as much as 13–14°F higher than corresponding groundwater temperatures in wells hydraulically upgradient of Zone A (i.e., MW-26S).	Elevated groundwater temperatures provide another line of evidence demonstrating a significant heat flux is occurring beneath Zone A, and is influencing groundwater temperatures nearly 30 feet below the drum repository.	A large heat flux is present beneath Zone A. Some of this heat is being actively transferred to the underlying groundwater system causing groundwater temperatures to exceed 29°C (~85°F). Short-lived, oxidative biodegradation processes involving thermophilic bacteria cannot account for this significant Zone A heat flux.
Use of Isotopic Indicators to Differentiate Combustion from Biological Processes	Not addressed by the IWAG as a combustion line of evidence.	Isotopic analysis was used during the 2012 Zone A Heating Evaluation to help differentiate combustion-generated gases from biologically generated gases; no IWAG rationale was provided for excluding isotopic gas analysis as a credible, core line of evidence to evaluate potential combustion beneath Zone A.	Not addressed by the IWAG as a combustion line of evidence.	Isotopic indicators were a cornerstone of the IWAG's 2012 Zone A Heating Evaluation, yet are not used in support of the 2017 combustion report. Some of the same authors and technical representatives were involved with both evaluation efforts.	Isotopic analysis is not viewed by Ecology as a reliable or technically defensible line of evidence that can reasonably override or counter the multiple lines of evidence indicating the likely occurrence (present or past) of subsurface smoldering combustion beneath Zone A.	The IWAG's decision to exclude the use of isotopic indicators as a key combustion line of evidence suggests inherent technical weaknesses associated with this evaluation metric.

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MEMORANDUM

DATE: May 25, 2017

TO: Mr. Charles Gruenenfelder, Ecology

FROM: Mr. Todd Thalhamer, PE

RE: Preliminary Review for Pasco Sanitary Landfill NPL Site / Zone A - Combustion Evaluation Report, Pasco Sanitary Landfill, Washington, April 25, 2017, 17800-69

Per the Washington State Department of Ecology (Ecology) request for technical assistance, I have reviewed the Zone A Combustion Evaluation Report for the Pasco Sanitary Landfill and have evaluated existing information on Zone A subsurface conditions and ongoing soil vapor extraction (SVE) operations; temperature data; subsurface gas composition; boring and historical well logs; ground settlement information; historical temperature profiling information; and related documents, reports, data, and photographs. On May 8, 2017, I attended a site walk with Ecology at the Pasco Landfill Zone A.

Discussion

The Industrial Waste Area Generator Group III (IWAG) consulting group proposed six combustion metrics with results and analysis to determine if combustion is present at Zone A. These metrics were then used to create "Lines of Evidence" indicating if combustion is present. Several of the lines of evidence were taken from Landfill Fires: Their Magnitude, Characteristics, and Mitigation (FEMA 2002) and Jafari et al. (2017a). According to the IWAG consulting group (IWAG 2017), the lines of evidence include the metrics in Figure 1 (Table 2.1. Lines of evidence to evaluate if combustion is occurring in Zone A).

Figure 1. Lines of Evidence in the Zone A Combustion Evaluation Report (IWAG 2017)

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.*

Note: Metric 7 was not discussed in the IWAG's report due to the lack of results at the time of publication.

Smoldering Fires

To discuss these lines of evidence one must have a general understanding of smoldering fires in combustible wastes. A landfill operator can either increase or decrease the potential for a smoldering event with how the waste is covered, compacted, and/or controlled. A typical subsurface fire starts from overdrawing a gas collection system. Smoldering fires can also start from actions that allow oxygen to enter the waste prism such as fissures, rapid settlement, an abandoned gravel access road, poorly compacted or inadequate interim/final covers, uncapped borings, passive venting systems, or other poorly installed environmental controls. The events usually occur on slopes, at changes in slopes, areas with poor interim cover, and/or areas within the influence of the gas extraction system.

The waste mass tends to oxidize around or near a surface feature that allows oxygen to enter the waste mass. These fires are more likely to burn slowly without visible flame or large quantities of smoke and are characterized by rapid oxidation of organic waste. At times, oxidation/combustion will go undetected until a sinkhole or smoke appears. While observing smoke or steam is typically most common method in detecting a subsurface fire in a landfill (Moqbel 2010), other signs of combustion are usually present in the gas control data (Jafari 2017b). Normally an individual will not see actual flame or dark black smoke during smoldering events unless the subsurface fire is excavated or exposed to the atmosphere.

To assess how a landfill combusts, environmental conditions and field indictors must be examined. Combustion is an exothermic oxidation reaction that generates detectable heat and light (DeHann 2007). One should note that the definition of light is not limited to our visible spectrum. For example, when hydrogen and methanol burn they result in fires that are not visible to the human eye. Also, other physical factors such as visible smoke are not reliable indicators of a fire. For example, a methanol fire and a properly stoked, charcoal barbeque fire both lack smoke. The absence of smoke is not evidence to preclude a smoldering or a flaming fire. Additionally, for burning or combustion to occur the following conditions must be present:

- A combustible fuel (e.g., a substance that can be burned to provide heat);
- An oxidizer (such as oxygen in air) must be available in sufficient quantity;
- Energy as some means of ignition (e.g., heat) must be applied; and
- The fuel and oxidizer must interact in a self-sustaining chain reaction.

The first three can be described as the fire triangle but the fourth must be present if the fire is to be self-sustaining (DeHann 2007).

In the landfill environment, combustion can be broken down into two types: 1) flaming and 2) smoldering (DeHann 2007; Martin et al. 2011b). While the first type of combustion is usually obvious, except for the visible light spectrum circumstances, the second type of combustion can cause investigative errors or lead to creative terminology to avoid using the term fire (Thalhamer 2011). Unless one excavates a smoldering fire, the signs of a smoldering fire may be obscured by the environmental conditions of a landfill (Martin et al. 2011a). As depicted in Photo 1, the signs of a smoldering fire are not always readily apparent to the human eye. During a San Francisco landfill fire investigation I conducted, a vent temperature of 480 degrees Fahrenheit (°F) was measured with no visible signs of smoke.

Most of the time operational decisions will determine whether a smoldering fire will ignite. The single most important factor in reducing smoldering fires is to limit the availability of oxygen present in the waste mass. To control the available oxygen, operators should use best management practices (Ohio 2011) regarding compaction, cover, waste profiling, maintenance, and gas control. If implemented correctly, the likelihood of starting a smoldering fire will remain low. The most common causes of a smoldering fire are the overdrawing of a gas collection system (LandTec 2005a and 2005b).

Photo 1. Smoldering subsurface event at Candlestick State Park, California (Source: Todd Thalhamer 2006).

The waste mass tends to oxidize around or near a surface feature that allows oxygen to enter the waste mass. Most subsurface fires in gas collection systems are detected by elevated temperatures at the well head or by the detection of carbon monoxide (CO) or soot in the gas collection system (LandTech 2005a). These fires are more likely to burn slowly without visible flame or large quantities of smoke and are characterized by rapid oxidation of organic waste. At times, this combustion/oxidation will go undetected until a sinkhole or smoke appears. Photo 2 shows a typical sinkhole related to a subsurface smoldering event. Normally, an individual will not see actual flame or dark, black smoke during smoldering events unless the subsurface fire is excavated or exposed to the atmosphere.

Photo 2. Typical sinkhole at a solid waste landfill caused by a subsurface smoldering event (Source: Todd Thalhamer)

Based on several of my training seminars and other discussions with landfill operators and consultants, there are several misconceptions about smoldering combustion. Over the years, the general belief in the industry has been that smoldering fires need oxygen above 15 percent by volume and temperatures above 450°F to 480°F to propagate. While the ignition temperature of wood is around 480°F (Babaruskas 2003a), it has been documented that temperatures as low as 170° F for time periods of several months to several years have ignited wood (Babaruskas 2003b and 2003c). Additionally, smoldering fires will propagate at oxygen concentrations below 3 percent (DeHann 2007) and have been documented to persist within a solid waste landfill between 212°F and 250°F (Ettala et al. 1996). Recognition of these facts is critical to understanding the potential consequences of overdrawing a gas extraction system.

Spontaneous Combustion

The bacteria, both aerobic and anaerobic, present in organic matter require water (H_2O) to biologically breakdown organic matter. As anaerobic bacteria biodegrade the organic material, heat (Δt) is produced along with degraded organic matter, methane (CH_4), carbon dioxide (CO_2) and other gases.

$$\text{Organic Matter (solid waste)} + H_20 \xrightarrow[\Delta t]{\text{Bacteria}} \text{Biodegraded organic matter} + CH_4 + CO_2 + \text{Other gases}$$

In spontaneous combustion, waste material is heated by biological decomposition and chemical oxidation. The temperature at which the waste is heated depends on the type of bacteria present. Two types of bacteria dominate in solid waste landfills: mesophilic and thermophilic bacteria. The literature indicates that most landfills operate in the mesophilic range, although optimum landfill gas production is achieved within the thermophilic range. Each type of bacteria has a unique operating temperature. Generally, mesophilic bacteria grow in a temperature range of 77 to 104°F (20 to 45 degrees Celsius [°C]) with an optimum temperature of 95°F (35°C), while thermophilic bacteria grow in a temperature range of 104 to 167°F (45 to 75°C) with an optimum temperature of 131 to 149°F (55 to 65°C).

Spontaneous combustion in waste is analogous to chemical self-heating of hay. This process involves three separate reactions: (1) decomposition; (2) chemical oxidation; and (3) Maillard Reaction (US Fire Administration 1998; Ontario Ministry of Agriculture, Food, and Rural Affairs 1993). The Maillard Reaction is a non-enzymatic reaction between sugars and proteins that occurs upon heating and produces browning. The resulting heat from these three reactions causes the material to reach the point of ignition. This rapid oxidation in a municipal or construction/wood waste facility is directly related to the type of bacteria and amount of moisture and oxygen present in the fill. With the correct conditions present, spontaneous combustion can occur in household trash and construction debris. This type of smoldering combustion will produce excessive amounts of CO and other trace toxic gases.

Confirming a Landfill Fire

Generally, to confirm a subsurface fire, one must have visual confirmation or other physical conditions present. A subsurface fire in combustible waste can be confirmed by:

- Substantial settlement over a short period of time;
- Smoke emanating from the gas extraction well, sink hole, or landfill fissure;
- Combustion residue (carbon soot) in extraction wells, headers, and/or screens at the flare inlet; and
- Landfill temperatures more than 176°F and/or levels of CO more than 1,500 parts per million by volume (ppmV) with one of the above indicators.

The above reactions are dependent on several factors at a facility including: waste composition, moisture content, temperature, oxygen, compaction, landfill operations, leachate recirculation, Landfill Gas (LFG) operations, cover properties, barometric pressures, waste cell construction, and other environmental issues. If a landfill's gas extraction system is not properly adjusted or the cover is not properly compacted, excess oxygen can be introduced into the waste cell. A facility may also unknowingly accept a reactive waste. These types of factors can negatively impact the biological process or directly cause a landfill fire.

One parameter, such as CO in excess of 1,500 ppmV, can be sufficient to determine if a smoldering landfill fire is present; generally, however, multiple parameters should be used to confirm a smoldering event is occurring. Smoldering combustion has been shown to produce CO concentrations of 1 to 10 percent (10,000 ppmV to 100,000 ppmV), where flaming combustion generally produces less than 0.02 percent (200 ppmV) CO (DeHann 2007). Other landfill fire literature uses CO concentrations as low as a few parts per million to 100 ppmV as a possible positive indicator of a landfill fire (Waste Age 1984; Environment Agency 2004; Industry Code of Practice 2008). Based on other landfill fire evaluations and case studies, other processes may produce CO at these concentrations (Martin et al. 2011b) and therefore one should use the higher CO concentration of greater than 1,500 ppmV as the threshold value to prevent false assumptions.

After years of the examining CO results and working with multiple data plots of CO versus CH_4 (Stark 2013) from subsurface events (SSEs), levels of CO over 1,500 ppmV can still be an indication of an SSE if other trends in the data and/or physical signs are observed. Typically, CO from active smoldering events range from 1,000 to 9,000 ppmV and have been documented as exceeding 28,000 ppmV as the smoldering event breaks through the surface. Just as in using landfill temperatures to evaluate the smoldering event, CO readings should also be examined over time and trend plots developed. Similar to temperature, CO from a smoldering event will reside in the waste prism for an extended amount of time. While elevated temperatures can remain over 18 to 24 months and longer, CO concentrations will begin to drop within 1 to 6 months as the smoldering event diminishes. Since the waste is not homogeneous and other waste management practices (e.g., compaction, leachate recirculation, types of waste, daily cover, waste cell size, access roads, gas extraction collection and rates, etc.) may be found to vary across the landfill, some monitoring points will not show high CO while others directly adjacent will show high CO. The entire suspected area and monitoring points should be examined on a continuous timeline to draw conclusions.

It is also important to understand that waste temperatures control the quality and quantity of landfill gas generated (Hanson et al. 2010; Crutcher and Rovers 1982) and are an important factor in determining if a landfill fire is present. Some published literature (Meima et al. 2008) and federal regulations (New Source Performance Standards) consider temperatures over 131°F (U.S. EPA 1999) as an indication of a heating event.

For this evaluation:

- Temperatures over 165°F will be used as an indicator of a heating event and not as confirmation of a fire;
- Once temperatures exceed 176°F, methane production typically stops (Martin et al 2011b; Thalhamer 2011) and further evaluation is warranted;
- Between 212°F and 250°F subsurface smoldering will persist in an MSW landfill as documented in a previous study (Ettala et al. 1996);
- If temperatures are reproducible and above 300°F in a municipal solid waste (MSW) landfill, this temperature confirms a fire based on my experience; and
- Should landfill temperatures be below 300°F, then multiple parameters such as CO readings should be collected or landfill gas ratios of CH_4 to CO_2 plots should be used as confirmatory evidence of an SSE or fire.

Heat generated from a smoldering fire or reaction can damage the environmental control systems of landfills. Elevated temperature in a MSW landfill can pose health, environmental, and safety risks because the elevated temperature can generate excessive gases, pressure, and damage landfill infrastructure. Elevated temperatures have been documented in MSW landfills, construction demolition debris landfills, industrial waste fills, and sanitary dumps (Martin et al. 2012; Sperling and Henderson 2001; Hogland and Marques 2003; Ettala et al. 1996; Riquier et al. 2003; Øygard et al. 2005; El-Fadel et al. 1977; Merry et al. 2005; Koelsch et al. 2005; Frid et al. 2009). The presence of elevated temperatures, particularly in MSW landfills, can impact the integrity of the cover and liner systems, leachate quality, gas composition, slope stability and differential settlement, odor mitigation, and abatement operations (Lewicki 1999; Øygard et al. 2005; Jafari et al. 2014a; Stark et al. 2012). Research has shown sustained temperatures as low as 185°F have impacted the service life and integrity of landfill gas extraction systems, leachate control systems, covers, and materials in composite liner systems (Rowe et al. 2010). Some PVC piping will fail as low as 165°F (SWANA 1997).

Several factors can lead to landfill temperatures above 149°F, including aerobic decomposition, self-heating, partially extinguished surface fires, exothermic chemical reactions, spontaneous combustion, and smoldering combustion. MSW landfills have experienced elevated temperatures due to possible exothermic chemical reactions of industrial wastes, including aluminum production wastes, incinerator and bottom ash (Klein et al. 2001; Klein et al. 2003), tires (Wappett and Zornberg 2006), iron waste, steel mill slag, petroleum coke, flue gas desulfurization gypsum, fluidized bed combustion residues (Anthony et al. 1999), lime kiln dust, and dried wastewater sludge (Zerlottin et al. 2013).

In addition to heat, other combustion by-products including gases, vapors, and smoke will be produced by a landfill fire. These by-products can also be used to evaluate whether a landfill fire is present. A landfill fire will emit air pollutants including, but not limited to, particulate matter, CO, volatile organic compounds (VOCs) (e.g., benzene, and methyl-ethyl ketone), Polycyclic Aromatic Hydrocarbons (PAHs), semi-volatile organic compounds (SVOCs), chlorinated dibenzo-p-dioxins, and chlorodibenzofurans, that can pose safety and environmental health threats (Martin et al. 2011a; Stark et al. 2012; Szczygielski 2007; Bates 2004; Nammari et al. 2004; US EPA 2002; ATSDR 2001).

Smoldering combustion at waste facilities has also been shown to increase the concentration in some VOCs (e.g., benzene and methyl-ethyl ketone) one to two orders in magnitude (Martin et al. 2012; Parker et al. 2002). In general, gas concentrations of some VOCs emissions from Subtitle D landfills double with every 18°F of temperature increase (ATSDR 2001). Benzene and methyl-ethyl ketone are two compounds that have consistently been found at elevated levels during landfill fire investigations. These compounds can be used to examine the likelihood of a landfill fire in conjunction with other parameters (Thalhamer 2011).

Of the smoldering events that I have evaluated, all have pre-indicators in the landfill gas control data. To date, I have not observed an SSE at a landfill with an active gas collection system that has just appeared. The data relating to SSEs has always involved decreases and increases in landfill gases and temperatures. While the changes in the data might not initially be significant, when a trend analysis is performed over a significant period of time, cautionary trends can be observed. The operator should closely monitor data for increasing oxygen and temperatures over time and the ratio of CH_4 to CO_2.

Industry Standard Operating Procedures

To gain additional knowledge of smoldering fires one should review the policies on how industry manages gas control systems through their standard operating procedures (SOP). By evaluating SOPs and design manuals for landfill gas management, one can understand how the industry meets the laws and regulations to properly control landfill odors, gas migration, and prevent landfill fires/subsurface smoldering events. These SOPs can also provide guidance on managing smoldering events and best management practices. The following SOPs and design documents were consulted on gas collection and prevention of landfill fires:

- Landfill Gas Management Standard Operating Procedures, prepared by Republic Services, Inc., dated May 1, 2009;
- Operations Manual for the Landfill Gas Collection and Control System at the Washington County Landfill, Washington, Utah, prepared by Cornerstone, dated October 2011;
- Brawley Solid Waste Site Landfill Gas Collection and Control System, Operation and Maintenance Plan, prepared by Geosyntec Consultants, dated April 2012;
- Landfill Gas Operation and Maintenance, Manual of Practice, Solid Waste Association of North America (SWANA), dated March 1997;

- Field Procedures Handbook for the Operation of Landfill Biogas Systems, prepared by the International Solid Waste Association (ISWA), Working Group of Sanitary Landfills, dated Winter 2005;
- Landfill Gas Management Facilities Design Guidelines, prepared by Conestoga-Rovers and Associates, Ministry of the Environment (ME), British Columbia (BC), dated March 2010;
- Guidance for Evaluating Landfill Gas Emissions from Closed or Abandoned Facilities, prepared by the U.S. Environmental Protection Agency (US EPA), dated September 2005;
- Landfill Off-Gas Collection and Treatment Systems, Engineering Manual, prepared by the U.S. Army Corps of Engineers (USACE), dated May 2008; and
- Higher Operating Value Demonstrations, prepared by the Ohio Environmental Protection Agency (Ohio EPA), dated September 2016 (updated December 2010).

As expected the procedures to detect, evaluate, and mitigate a landfill fire vary among the documents, however, there are a number of common criteria. Table 1 summarizes industry SOPs and other documents on landfill operations and prevention of fires.

Table 1 - General Parameters for Landfill Operations and Prevention of Fires

Document Author	Recommended /Allowed Oxygen Intrusion	Normal and Action Level Methane Range	Temperature Action Range	Carbon Monoxide (CO) Action Level	Symptoms/Indications of a Smoldering Event or Comments
Republic Services	<1% typical <2% Max	Normal: Arid 43-48% Non Arid 48-52% Action Level: <48%	>120°F Temperature exceeding an est. variance >20% from historic temperature	>300 ppmV	• Dramatic localized landfill settlement • Charred or cracked surface cover • Stressed or dead vegetation • Smoke or smoky odor • Drastic or unusual increase in flowing gas temperature • Abnormal discoloration of a wellhead/riser
Cornerstone	Hold at 0.2% Never allowed to exceed 1%	Normal: 50% to 70% Action Level <47% Extreme well stress <40%	Should not exceed 130°F	CO near a subsurface fire may vary from 100 to 1,000 ppmV	• Smoke emitting from landfill cover openings • Extraordinary and rapid subsidence of a localized landfill area • Presence of CO in the extracted LFG.
Geosyntec Consultants	<5%	*No Information*	>140°F	>1,000 ppmV	• Gas temperatures exceeding 167°F and CO greater than 1,000 ppmV are indicators of a potential fire

Document Author	Recommended /Allowed Oxygen Intrusion	Normal and Action Level Methane Range	Temperature Action Range	Carbon Monoxide (CO) Action Level	Symptoms/Indications of a Smoldering Event or Comments
SWANA	Ideal 0 to 0.5% <1%	Normal: 45 to 58%	Typical range: 60ºF to 125°F Action range: 125ºF to 140°F	Trace <25 ppmV	• CO is an indicator of the possible presence of a subsurface fire • 165°F is the temperature limit for PVC • CO is a by-product of incomplete combustion and an indicator of a possible subsurface fire • Landfill fire may be tested by monitoring CO • Best way to treat a LFG fire is to starve the fire of oxygen • High residual nitrogen gas (N_2) levels may indicate a landfill fire • If oxygen is sufficiently high (around 10% or greater) the LFG can be in the combustible range within the collection piping
ISWA	3 to 4%	Normal: 35 to 50%	*No Information*	*No Information*	• Operators should also periodically monitor for the presence of high levels of residual nitrogen since this could indicate conditions that could spark a landfill fire • Operation of extraction wells at temperatures greater than 145°F may result in the weakening and possible collapse of thermoplastic well casings
ME-BC	2.0% Shall not exceed 2.5%	Normal: 30 to 60%	Action Level: >140°F	>1,000 ppmV	• Active LFG collection areas that are overdrawn and may have too much available vacuum being applied to the well field • Monitoring data shows high O_2, high CO (>1,000 ppmV), and high LFG temperature (>140°F) • Accelerated landfill settlement in localized areas • Impacted infrastructure such as melted wellheads or piping • Smoke, odor, or residue • A landfill fire may be officially confirmed through the use of field equipment monitoring and laboratory testing for incomplete combustion compounds such as CO • While an effectively-operated LFG management system can be a fire prevention system, inappropriate operations can pose a fire risk

Document Author	Recommended /Allowed Oxygen Intrusion	Normal and Action Level Methane Range	Temperature Action Range	Carbon Monoxide (CO) Action Level	Symptoms/Indications of a Smoldering Event or Comments
US EPA	Typical 0.1 to 1% Max. <5%	Normal: 45 to 60%	Action Level >130°F	0 to 2,000 ppmV	• Landfill fires can occur from the excessive influx of ambient air into the landfill wastes • Underground landfill fires generally occur when ambient air is drawn into the landfill • There must be data demonstrating that the elevated parameter(s) does not cause fires or significantly inhibit anaerobic decomposition of the waste (40 CFR §60.753)
USACE	Increasing and exceeds 3.2%	Normal: 40-70%	Optimum 85ºF to 105ºF Action Level increasing and exceeds >140°F	>1,000 ppmV	• CO can be monitored as an indicator of a landfill fire if the gas temperature begins to rise • If a fire occurs, fire control may be accomplished through the injection of nitrogen or CO_2 into the landfill to suffocate the fire. The following parameters are evidence of fire within the landfill: • Gas temperature >167°F • Rapid settlement of the cover system • CO levels are >1,000 ppmV • Combustion residue is present in the LFG lines
Ohio EPA	No more than 1.5% oxygen for an HOV (Higher Operating Value) request	Action level: No less than 45% methane for an HOV request	Gas temperatures at or below 150°F for an HOV request	CO with no more than 100 ppmV for an HOV request	• Excess nitrogen may be associated with the consumption of oxygen • CO is a good indicator for the presence of fires in a waste mass • Agrees with the National Solid Waste Management Association that when methane content of a wellhead drops below 45%, then "something" adverse is happening

Lines of Evidence to Evaluate Potential Combustion

The combustion study discusses several lines of evidence to evaluate whether combustion is occurring beneath Zone A. For brevity, each section will be discussed based on the review of the project files, past smoldering events, and my site visit on May 9, 2017.

Evidence Synopsis

Overall one critical line of evidence was left out of the review of Zone A. The IWAG group failed to recognized the two areas of substantial settlement and one minor area to the east in their discussion concerning a possible combustion event. As discussed previously, a smoldering fire in combustible waste can be confirmed by several factors including substantial settlement over a short period of time. The two main settlement areas within Zone A are key to understanding the phases of combustion in a landfill. Based on past settlement in MSW landfills, one can predict the general direction and level of activity. Figure 2 shows the two main areas of settlement greater than 5 feet. Without data collected directly from these areas, the reported temperature and CO data can be ambiguous and questionable if one examines the waste layers in Zone A. As discussed by the IWAG consulting group, the landfill has multiple layers of waste, soil, concrete, tires, debris, pockets of mixed debris, and stacked and randomly placed drums.

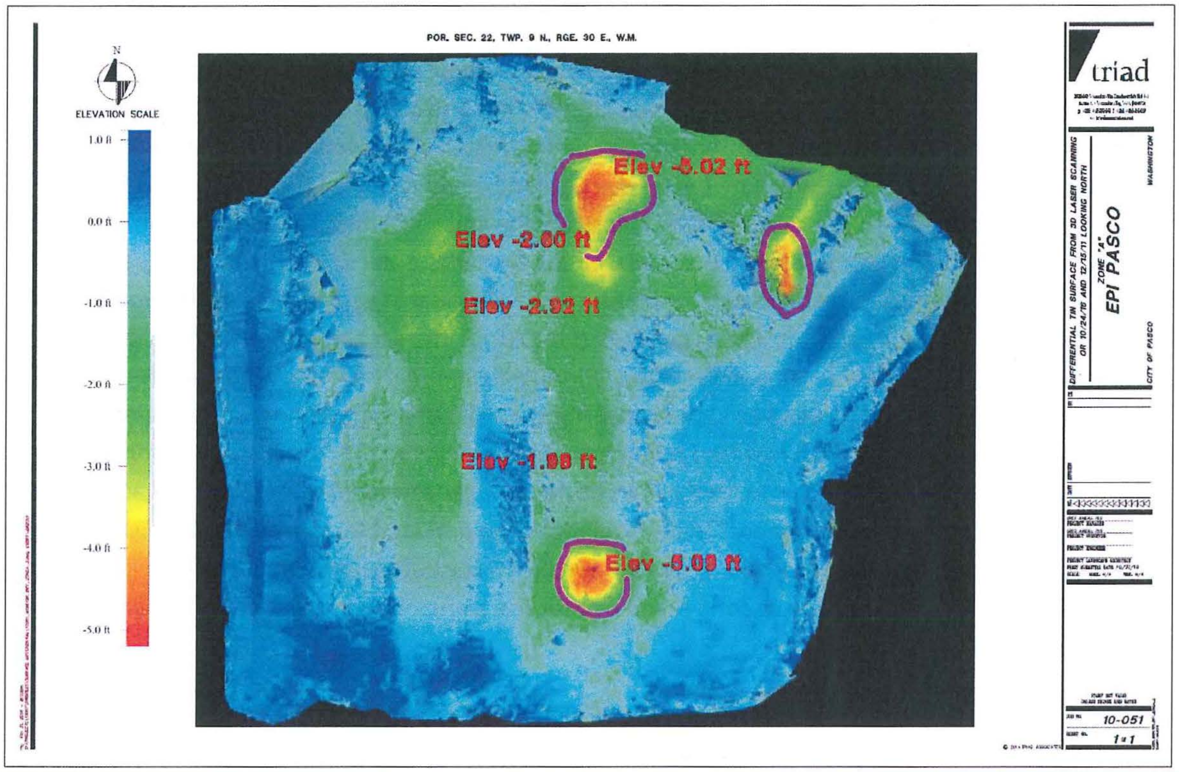

Figure 2. Triad December 2011 through October 2016 Lidar Settlement Map

This waste composition component and settlement are fundamental to understanding the lines of evidence. From my prior landfill fire experience, the two main areas of settlement are very suspicious in nature and with the data collected in March 2017, are typically enough to confirm the presence of combustion. As to the stage of the combustion, one would need to collect additional data from the western edge of the settlement to determine if the combustion was active. If the data reveal combustion is not active, additional real-time monitoring should be used to prevent combustion from occurring.

Visual Observations of Smoke

While visible smoke is a confirmation of a combustion event at a landfill, the lack of smoke does not prove the absence of combustion. As stated previously, smoke may not be visible at a landfill based on environmental conditions and/or controls. Should smoke be pulled through several layers of soil and debris, say by an SVE, the smoke particles will stick to substrate and act as a filter. As Photo 1 depicts, some field indicators of combustion can be present while other observations are not present. The IWAG's consulting group proposed evidence that "since smoke is a confirmatory indicator of subsurface combustion and smoke and embers have been observed in Zone A there is not combustion" is not valid.

In-Situ Soil Temperatures

While the IWAG consulting group rely on several publications to discuss the *in-situ* soil temperatures, it is important to point out that they relied on three key references from non-peer reviewed publications. The three references are a presentation and article for Waste360, and a web reference to a $1 million grant by a waste industry think tank (Environmental Research and Education Foundation 2016). This organization funded a research project titled: Understanding and Predicting Temperatures in Municipal Solid Waste Landfills. The first reference is a presentation by Barlaz et al. (2016a) and not a publication. This reference states "Experts in elevated temperatures landfills state that "*the literature suggest that biological reactions may result in landfill at perhaps 160-170°F.*" The second reference (Barlaz et al. 2016b) states that "...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). As pointed out by both non-peer reviewed references, the authors use the terms "may" and "can be erroneous" in determining if the detected temperatures and CO results can be used as indicators of combustion. However, the IWAG consulting group fail to recognize the other physical signs of combustion at Zone A and did not use some of their own field collected waste temperatures.

The IWAG consulting group suggest that the data collected to date is below the upper biodegradation temperature level for solid waste of 176°F and below the 392°F ignition point of solid waste. The IWAG consultant group did not use the recorded waste temperature in borings to make this statement. The recorded temperatures were well above the upper limits of biological decomposition in several borings. For example, in Table 2 a number of borings indicated *in-situ* waste temperatures above the upper biodegradation level for solid waste of 176°F.

Table 2 - Examples of Elevated Temperatures (>176°F) at Pasco Landfill in Waste Borings

Boring ID	Date	Temperature Exceptions °F
GI-1	1/5/2017	179, 196,195, 177, 185, 203, 177,185, 186, 191, 194, 195, 183, 188, 196, 206
GI-2	1/17/2017	186, 193, 198, 201, 183
GI-3	1/18/2017	194, 197, 184, 182, 189, 182, 197, 196
TC-4	1/24/2017	180, 182, 190, 183
GI-4	1/24/2017	200, 206, 196, 201, 196, 192, 187, 181
GI-5	1/9/2017	191, 202, 203, 201, 197, 178, 183, 196, 195, 192
		204, 195, 192, 196, 186, 184, 200, 203, 204, 204, 199, 187, 202, 203, 202, 186,
TC-6	1/23/2017	199, 202, 179, 180, 192, 192, 198

While these record temperatures cannot confirm the present of combustion, one should not discount them in the lines of evidence (Jafari 2017b). Since the vast majority of the temperature data points were collected in soil and debris matrices outside the settlement areas, the temperature data may not be representative of current combustion conditions in the sink holes. Additionally, based on the data from the 2014 Balefill Fire (See Figure 5.5 in the Zone A Combustion Study), smoldering fronts can present temperatures over 700°F in thermocouples, yet insulating properties of mix waste and soil can prevent thermocouples 10 feet away from detecting heat and the smoldering front. The proposed evidence that "since the maximum *in-situ* temperatures recorded were 159°F during the main test does not support combustion" is not valid.

Carbon Monoxide Concentration

The most recent CO data collected on March 29, 2017, is both concerning and validating based on my experience. The two readings of CO over 1,000 ppmV (Table 3) are red flags for smoldering events at landfills. If the CO trend continues upward the likelihood the facility has an active smolder is high. Additionally, the same conditions apply to the collection of CO data, the farther away the data are collected in waste that is not homogeneous (i.e., mixed pockets of debris, soil, concrete, etc.), the likelihood of accurate CO data are low for a localized combustion event.

Table 3 - Carbon Monoxide Data from Pasco Landfill, March 2017

Location	Date	CO Readings in ppmV
GI1-35	3/29/2017	**1,214**
GI2-27	3/29/2017	597
GI2-32	3/29/2017	841
GI3-25	3/29/2017	795
GI4-30	3/29/2017	15
GI5-28	3/29/2017	930
GI6-29	3/29/2017	**1,416**
GI8-37	3/29/2017	1,002

The detected CO readings above 1,000 ppmV warrants further evaluation. While the 1,500 ppmV threshold of CO with other factors can be used to confirm combustion, detection of the recent high CO readings points to active combustion. Additional samples should be collected to determine the stage of combustion. The CO evidence points towards potential combustion and does not exclude combustion.

Carbon Dioxide/Characteristics of Mixed Debris Layers/Total Volatile Solids in Mixed Debris

Based on a review of the file and my waste industry experience, the likely fill pattern at the Zone A landfill would include a few mixed waste pockets along with layers of non-combustible soil and debris. Once the drums were segregated from the incoming waste stream, it is logical the facility would have placed soil and combustible waste in pockets next to the drums to fill in the space between the randomly placed and stacked drums. This conceptual model has been proven by the site borings and logs. While I am not an expert on the observed CO_2 to O_2 relationship nor the previous isotopic analysis to confirm the presence of combustion, if the data collected in these studies is not within the suspected areas of combustion, other fill materials and hazardous waste could potentially interfere with the possible outcomes. To correctly use the other possible new combustion investigative techniques at landfills, the data should be collected from the area of settlement and in the pockets of mix combustible debris.

It has been reported by industry that if waste material does not show signs of charring there must not be a fire. One must realize that this is a macro statement and even if the material is not chocolate or black in color, other changes in the waste color may point to pre-combustion/chemical oxidation events. Again, examining the self-heating hay fire shows a gradation of color as you approach the char. The hay would go from greenish-brown to golden brown to dark brown to chocolate to black and then may ignite given the available oxygen. While color changes in the waste, except for the obvious black char, cannot confirm a landfill fire, color changes should be noted and may either lead to the area of a smolder or the area has been impacted by chemical oxidation or pre-combustion.

While the mixed debris layers, CO_2 to O_2 relationship, and total volatile solids in mixed debris discussions may have some validity for a homogenous waste mass, the IWAG consulting group did not perform the sampling in the two areas that may or may not have proven these theories valid. Until such data are collected from these sink holes the evidence does not support the conclusion of no combustion.

Recommendations

Just as recently as September 14, 2012, the IWAG consulting group stated in a Memorandum (Anchor 2012) to Mr. Gruenenfelder of the Washington Department of Ecology from SCS Engineers, Anchor QEA, and Environmental Partners that there are six key indicators of a heating event related to subsurface combustion in landfills. Since Zone A is an industrial waste landfill, these indicators would be useful in evaluating this landfill. The consultant group listed *"In approximate order, from the most readily visible/easily discernible (which is physical settlement) to indicators requiring invasive measurements or testing, these are:*

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

According to the IWAG consulting group, "These indicators are widely accepted as indicators of subsurface heating events related to combustion. Indicators, such as settlement, smoke, CO, combustion residues, and subsurface soil and gas temperatures are equally applicable to MSW landfills, construction and demolition debris (C&D) landfills, and industrial waste landfills." Unfortunately, the consultant group did not follow its own recommendations and overlooked the two or three areas where the potential for combustion is the highest. Based on conversations with Ecology, the IWAG consulting group was concerned with collecting data from the sink holes given the proximity to buried drums. It is my opinion the data can be collected safely from the western edge of the settlement, away from the drums with minimum risk to the environment when compared to the continuation of a smoldering event.

Until additional data are collected at the three areas of subsidence as previously discussed, I suspect pockets of mixed waste in Zone A are combusting, has combusted, and/or may be in stages of pre-combustion. Also, I recommend the SVE operation be limited to the shallow and deep wells until additional data are collected.

Summary

The combustion study proposed a number of lines of evidence "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 Soil Vapor Extraction (SVE) system operation." Unfortunately, not all the lines of evidence demonstrate that combustion is not occurring in Zone A, and in fact combustion may have already occurred in three locations in Zone A and may still be occurring based on a number of field observations and/or combustion indicators from the referenced documents. In order to determine the status of combustion, the IWAG consulting group should evaluate the western edges of the two main areas of subsidence as shown by the December 2011 through October 2016 Lidar settlement map. Both these areas are likely similar to the pockets of mix debris discovered between the "Randomly Placed Drums" and "Stacked Drums" at Zone A. Unfortunately, until these areas are evaluated for CO concentrations and temperatures, one should not state there are multiple lines of evidence that show combustion is not occurring in Zone A. In summary, I do not have a high degree of confidence that the conclusions by the consultants on behalf of the IWAG consulting group at Pasco Sanitary Landfill will not cause further damage to the landfill environmental control system or acerbate combustion mechanisms in the mixed debris.

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