EXPERT PANEL REPORT:

BRISTOL INTEGRATED SOLID WASTE MANAGEMENT FACILITY, BRISTOL, VIRGINIA

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Executive Summary

An Expert Panel ("Panel") was convened by the Virginia Department of Environmental Quality (DEQ) to address odor problems and operational concerns at the Bristol Integrated Solid Waste Management Facility ("Landfill") located in Bristol, Virginia. The charge to the Panel was to evaluate available data and information including actions over the history of the landfill and to provide recommendations to address these issues.

The Panel evaluated a substantial body of information including site maps prior to Landfill construction, pictures of Landfill construction, tables of odor complaints, gas and liquid sample data, input from local residents, and technical papers dealing with landfill odor problems similar to this site. The Panel inspected the Landfill and received presentations by several landfill experts with experience dealing with odors associated with similar landfill types at a meeting convened in Bristol on March 21-22.

This report summarizes consensus Panel recommendations pertaining to 1) mitigation of odors emanating from the Landfill; 2) feasibility of continued waste disposal operations of the Landfill; and 3) options for early closure of the Landfill; either temporary or permanent. The Panel also identified key data gaps that prevent a clear diagnosis of conditions and subsurface reactions in the Landfill and to verify performance of proposed engineered mitigation actions.

The Panel consensus was the Landfill is exhibiting early signs of an Elevated Temperature Landfill (ETLF) which is linked to production and release of odors. ETLFs are primarily characterized by temperatures in excess of 55°C (131°F) over a broad area for a sustained period of time and an atypical accumulation of heat. ETLFs are characterized by low methane content in the landfill gas, high leachate production rates, leachate with elevated concentrations of organic compounds, production of odoriferous gas, rapid settlement, and self-propagating reactions that generate heat. This condition has the potential to worsen unless prompt (immediate) action is taken.

1. The Panel recommended engineered actions intended to minimize the release of odors, reduce Landfill temperatures, and manage problematic conditions beneath the Landfill. This strategy includes preventing infiltration of precipitation and control and management of stormwater inside the Landfill. Specific recommendations are:
    - 1.1. Test and construct a sidewall odor mitigation system around the Landfill perimeter that will be designed and constructed to mitigate landfill gases emanating from the Landfill/quarry sidewalls.
    - 1.2. Improve the performance of existing gas extraction wells including minimizing air intrusion pathways through Landfill cover. Additional gas extraction wells will be needed to reduce emissions and temperatures.
    - 1.3. Identify and eliminate to the extent practical any landfill gas fugitive emissions at the Landfill surface. Weekly monitoring activities of gas emissions at the Landfill surface will be required.
    - 1.4. Install settlement plates and conduct monthly surveys to document the locations and rates of settlement in the waste mass.
    - 1.5. Install and monitor a dedicated system of thermocouples in the waste mass to monitor Landfill temperatures for greater spatial resolution (horizontal and vertical) and to provide data at a greater frequency.

1.6. Install at least five (5) deep dedicated monitoring wells to enable sampling and characterization of leachate and measurement of temperature profiles in the waste.
1.7. Install and operate large-diameter dual-phase extraction wells for removal of gas and leachate. Treatment requirements for extracted leachate must be determined.
1.8. Install a temporary geosynthetic cover over the entire Landfill. This will require substantial grading of the existing Landfill surface to direct runoff to the southeast corner of the Landfill where it is expected a stormwater management pond can be constructed to manage stormwater that is collected on top of the geomembrane cover.
1.9. Develop and implement an effective and sustainable stormwater management plan and settlement management plan for the Landfill.
1.10. The Panel recommended an active community outreach program to communicate strategies, provide status and progress reports, and receive citizen feedback.

2. The Panel considered two scenarios related to the feasibility of continued waste disposal operations: (1) waste disposal in a limited area of the Landfill while actions to mitigate odors were completed; and (2) installing a landfill dome over the Landfill. The Panel also considered a variation of (1) in which operations continued during an interim period followed by early closure of the Landfill.

2.1. Continuing Landfill operations while implementing the proposed remedial actions is problematic. Limiting operations to the northern end of the Landfill while addressing the ETLF condition in the southern area of the Landfill is not recommended.
2.2. The City should strongly consider a cessation of waste disposal operations at the Landfill due to incompatibility of operations with the necessary odor mitigation and ETLF remedial strategy. Short-term waste filling operations to shape the surface of the Landfill for the placement of the interim geomembrane cover must be carefully coordinated with engineers working on remedial actions.
2.3. The landfill dome option (or roof) is not recommended. A dome will be expensive, may not be resilient to major storms, and this concept does not have a sufficient track record for effective odor mitigation.

3. The Panel considered options for early closure including the feasibility of (1) installation of a permanent landfill cap at the current waste level following mitigation of odors and reduction of landfill temperatures; and (2) rapid fill of waste to the quarry rim followed by installation of permanent landfill cap.

3.1. Installing a permanent landfill cap designed to accommodate expected waste mass settlement without additional disposal of waste (other than shaping the Landfill surface) once odors and landfill temperatures are adequately reduced is a feasible option.
3.2. Rapid fill of the remaining permitted air space in the Landfill followed by a permanent landfill cap is not recommended given concerns for the ETLF considerations and cost considerations.
3.3. Resuming operations at the Landfill in the future may be technically feasible once the odors are controlled and ETLF conditions managed. However, there may be other technical, cost, and political considerations that would inform such a decision.

Expert Panel Report: Bristol Integrated Solid Waste Management Facility, Bristol, Virginia

1. Introduction

This Expert Panel Report was developed by an Expert Panel ("Panel") convened by the Virginia Department of Environmental Quality (DEQ) to address issues of public concern associated with the operation of the Bristol Integrated Solid Waste Management Facility ("Landfill") located in Bristol, Virginia. Beginning in 2020, local residents began experiencing and reporting odor issues, which have seemingly increased over time, despite mitigation efforts starting in 2021. Site data and observations related to the odors, including the composition and temperature of landfill gas, raised concerns that problematic conditions exist within the Landfill waste mass that should be addressed through engineered remedial actions.

The DEQ charged the Panel to evaluate available data including actions over the history of the Landfill and to consider options to mitigate odors and address related Landfill operations. This report summarizes consensus Panel recommendations to address the following three issues identified by DEQ in the Bristol Landfill Expert Panel Invitation dated March 1, 2022:

1. Excess odors emanating from the Landfill
2. Feasibility of continued waste disposal operations of the Landfill
3. Options for early closure of the Landfill; either temporary or permanent

Further, it was stipulated by DEQ that all options must be practicable (available and capable of being done after taking into consideration cost, existing technology, and logistics in light of overall project purposes).

Members of the Expert Panel are listed below. Addition information is provided in Appendix A, including a link to the DEQ website with biographical information of Panel members.

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The Panel met in Bristol, Virginia on March 20-22, 2022 for the express purpose of reaching a consensus on what the City of Bristol should do to alleviate Landfill odor emissions that are negatively affecting neighboring communities in Virginia and Tennessee. Prior to the meeting, site information and data related to Landfill operations, mitigation efforts to date, and monitoring data for landfill gas, leachate, and groundwater were provided to Panel members electronically. The meeting agenda is provided in Appendix B. The meeting was not open to the public. Representatives of the City of Bristol (City), Draper Aden Associates (DAA), SCS Engineers, and DEQ who are knowledgeable about the site and Landfill operations attended, answered site-specific questions posed by the Panel, and provided data and information relevant to the Panel charge.

Following an overview of the site by DAA and the City, the Panel visited the Landfill on the morning of March 21, 2022. The Panel engaged in discussions as a single body and within smaller groups to discuss findings and develop recommendations in relation to the panel charge. By the conclusion of the meeting on March 22, 2022, consensus was reached and a statement reflecting the outcome of the two-day panel meeting was developed. An email summary was transmitted to DEQ from the Panel Chair on March 28, 2022 (Appendix C).

This report consists of three main sections that summarize the following: Overview of Site Conditions; Findings; and Recommendations. The Expert Panel Recommendations address the three areas of concern identified by DEQ.

The Panel also identified key data gaps and data collection activities that are necessary to establish clear evidence of Landfill conditions and subsurface reactions causing odor emissions. An improved understanding of Landfill conditions is critical for the design and construction of remedial measures and for effective, sustainable long-term operation. The recommended data collection and monitoring activities are also designed to help verify the performance of proposed engineered mitigation actions.

This report reflects the analysis and deliberations of the Expert Panel over the two days it met and is not a comprehensive engineering report. The brevity of this report reflects the urgent need to implement Panel recommendations.

2. Overview of Site Conditions

2.1. Site Description and Summary of Landfill Operations

The Landfill is contained within a former limestone rock quarry located almost entirely in the city limits of Bristol, Virginia. The Landfill is located approximately one-quarter of a mile north of Bristol, Tennessee. The Landfill operates under Virginia Solid Waste Permit SWP No. 588 issued to the City in 1996 by DEQ. According to DEQ, the Landfill also operates pursuant to a Title V air and a minor new source review permit. The Facility is a Title V by rule source and is subject to NSPS WWW (Municipal Solid Waste Landfills) and MACT AAAA (Small Municipal Waste Combustors).

The Landfill (588) is one of three landfill units on 138 acres owned and operated by the City. The first landfill unit (Permit No. 221) is closed and capped. The second landfill unit (Permit No. 498) is currently being mined in order to recover airspace for potential future use as a construction and demolition debris (CDD) landfill. Mined materials are disposed in the active unit (i.e., Landfill). **Figure 1** shows the location of the three landfill units within the facility.

The Landfill began accepting waste for disposal in March 1998. The facility receives on average approximately 500 tons of municipal waste per day. The current active solid waste permit allows for disposal of up to 1600 tons per day. The total permitted landfill volume is 7,800,000 cubic yards (yd^3). The estimated unfilled volume of the permitted design capacity for the Landfill is approximately 4,000,000 yd^3.

The bottom of the Landfill is lined with a composite liner system consisting of a 60 mil thick high-density polyethylene (HDPE) geomembrane and compacted clay liner placed above a secondary compacted clay liner. The base liner system includes a 12-inch layer of crushed-stone to control groundwater, a 12-inch intermediate permeable witness zone, and an overlying leachate collection system consisting of 18-inch of permeable material. Compacted clay layers separate the various zones. The Landfill sidewall system consists of geocomposite drainage material, a 60 mil thick HDPE geomembrane liner and a non-woven geotextile which is attached to a wire mesh or chain link fencing connected to the quarry walls.

Quarry horizontal dimensions range from 1,500 feet (ft) at the base in the north-south direction to approximately 2,000 ft at the top rim. Lateral quarry dimensions range from 130 to 250 ft at the base to 430 to 650 ft near the upper rim of the quarry. **Figure 2** depicts the Landfill in plan view including current conditions (2021) of the Landfill land surface topography. **Figure 3** depicts cross-sectional views of the Landfill. The quarry ranges 325 to 350 ft in depth, with the pit floor at an elevation of 1550 ft and the rim at 1875 to 1900 ft. Based on the most recent available survey (2021), waste has been landfilled to depths ranging between 250 and 275 ft.

2.2. History and Nature of Odor Complaints and Mitigation Steps

In the latter months of 2020, the City and DEQ began receiving odor complaints from residents living in areas adjacent to the Landfill. The Panel received 15 letters from members of the greater Bristol community who have been impacted by odors derived from the Landfill. Residents described disruptions to their lives both inside and outside of their homes including parishioners' inability to conduct services in their place of worship.

DEQ began tracking odor complaints in December 2020. Two separate odor logs dating back to 2021 were made available to the Panel. The most frequently-reported odor complaint is chemical in nature. One resident described this as a chemical-smelling "smoke". This smell was readily apparent to Panel members during the site visit. Residents also frequently described the odors as rotting or sour garbage.

In response to a request from DEQ, the City engaged DAA to develop an odor management plan. The plan included the installation of 21 new gas extraction wells positioned throughout the Landfill. In December 2020, the City implemented immediate actions in response to odor complaints including working with SCS Field Services to design and construct upgrades to the existing landfill gas collection system in the Landfill. Installation of new wells begin in October 2021 and put into operation in December 2021.

2.3. Landfill Data and Information Considered

The Panel reviewed technical information related to Landfill operations and environmental data. These data included Landfill gas parameters, Landfill surface elevations and settlement data, leachate data, groundwater data, and deep well operating procedures. The Panel also evaluated the quantity and nature of historical landfill waste volume, waste density, and landfill volume projections to fill the remaining void and to enable landfill closure. Findings of the Panel related to Landfill data are discussed in the next section.

2.3.1. Landfill Gas Data

The Panel was provided Landfill gas data at the gas extraction wells starting in 2000 through March 2022. These data consisted of gas pressure and temperature and concentration of several components of landfill gas samples. Gas constituents relevant to this investigation are listed below. Landfill gas concentrations and in-situ gas temperatures are typically monitored at landfills as indicators of biological activity in landfill waste mass and the effectiveness of anaerobic decomposition of solid waste.

- Methane (CH_4)
- Carbon Dioxide (CO_2)
- Oxygen (O_2)
- Nitrogen (N_2)
- Hydrogen (H_2)
- Carbon Monoxide (CO)

Dating back to 2018, gas emissions were observed exiting the Landfill along the sidewalls between the quarry rock walls and the Landfill sidewall liner system. These point source emissions are referred to as "chimneys" which are present at various locations along the Landfill perimeter, specifically the eastern and western walls. Several of these chimneys were visible to the Panel along the western wall of the Landfill during the March 21, 2022 site visit. Gas composition data from chimney samples collected in January 2021 were provided to the Panel.

2.3.2. Landfill Settlement Data

In general, landfills are known to undergo settlement due to several internal mechanisms, resulting in the lowering of the ground or surface of a landfill over time. Settlement at the Landfill has been observed and reported. The Panel received topographic data from four top of waste surveys starting in June 2020 and ending in November 2021. Data consisted over approximately 300 survey points in a grid across the Landfill surface.

2.3.3. Groundwater Data

The Panel received a groundwater monitoring program report documenting two sampling events in 2020 in association with the Landfill permit (588). The 2020 Annual Groundwater Monitoring Report includes historical concentrations for constituents of concern including inorganics (metals), volatile organic compounds, including benzene, and semi-volatile compounds. The 2020 report documents water quality data in monitoring wells located upgradient and downgradient of the Landfill and in the gradient control outfall.

DAA reports show the quarry base elevation is approximately 200 ft below the current ambient piezometer surface in the limestone aquifer. The Landfill gradient control underdrain system draws and extracts local groundwater flowing into the quarry through a sump beneath the Landfill liner system that is hydraulically-connected to a "wet well" situated in a shaft drilled in bedrock. Accumulated groundwater in the wet well is continuously pumped as needed to maintain an inward gradient (flow of groundwater) to the quarry. Hence the name "gradient", referring to control of the local groundwater to induce an inward hydraulic gradient to the Landfill. Volumes of leachate and groundwater removed through the three pumps and wet well collection system from May 2021 through mid-March 2022 range from 0.2 million gallon per day (MGD) up to 0.5 MGD.

2.3.4. Landfill Leachate Data

The 2020 Annual Groundwater Monitoring Report includes water quality data for leachate and witness samples for the two sampling events and historical concentrations for constituents of concern. The Panel also received a report from Green Toxicology LLC which includes benzene concentrations in leachate and gradient liquid samples starting in 2011 to the present. The report documents the trend in increasing benzene concentrations with time starting in 2016.

DAA reported the depth to leachate within the Landfill is approximately 30 ft below the Landfill land surface (i.e., upper surface of saturated waste) during construction of new gas wells in 2021. Available data suggested that waste within the Landfill is saturated at vertical thicknesses approaching 200 ft. If confirmed, this finding would suggest that up to 300 million gallons of leachate could be present within the Landfill. There are currently no monitoring wells constructed within the Landfill to verify water levels in the waste mass.

3. Summary of Findings

3.1. Odor Generation and Elevated Landfill Temperatures

The Panel consensus was that Landfill odors are the result of a reaction taking place beneath the Landfill surface within the buried waste. The chimneys along the Landfill perimeter are likely the major avenue for release of these odors into the atmosphere. The presence of the chimneys suggest that the subsurface sidewall liner system has failed locally and the resulting poor contact between the Landfill liner and quarry sidewalls hinders containment of high-temperature landfill gases. The Panel agreed engineered remedial action can significantly reduce the release of odors around the Landfill perimeter. Regulatory approvals are needed to implement the proposed remedial approach involving any changes to the liner configuration.

The Panel concluded there is insufficient data to determine the degree to which odorous gas are seeping through the Landfill interim cover material into the atmosphere. However, the Panel considered the possibility that upward migration and release of landfill gas through earthen cover and commercial films spread over solid waste may be a contributing factor to odors. The Panel concluded this avenue of release must be immediately investigated.

The Panel noted elevated O_2 greater than 2% in a number of landfill gas wells. The source of the O_2 intrusion is either from leaks associated with the gas collection wellhead assemblies/ports or overdrawing of the landfill gas wells. Introduction of O_2 into the waste mass is not desirable because it can promote heat-generating subsurface oxidation reactions and spontaneous combustion of the waste mass, leading to an underground fire. This suggests the gas wells are likely pulling air through open or poorly-covered waste and landfill cover material which introduces atmospheric oxygen into the Landfill. The Panel concluded this pathway should be immediately evaluated and remedied to prevent further intrusion of oxygen into the Landfill. If sources of O_2 are not eliminated, the Panel noted that the potential for non-ideal conditions in the waste mass would increase, which would be detrimental to minimizing the Landfill odor problem. Further, the Panel noted that improved operation of landfill gas wells will contribute to improved removal of heat and landfill gas.

The Panel concluded that the Landfill is exhibiting conditions associated with an Elevated Temperature Landfill (ETLF). ETLFs are primarily characterized by temperatures in excess of 55°C (131°F) over a broad area for a sustained period of time. Other characteristics relative to those observed in municipal solid waste landfills include low methane content in landfill gas relative to CO_2 along with CO and H_2, high leachate generation rates; strong leachate with high biological oxygen demand (BOD), high chemical oxygen demand (COD), and concentrations of organic compounds (e.g., benzene) orders of magnitude above typical leachates; large and rapid settlements; and production of highly unusual and odoriferous gas. ETLF conditions are commonly identified in deep landfills with a thick mass of saturated waste.

The Panel concluded there are insufficient data to reach a consensus on identifying specific chemical reactions responsible for the generation of heat and odors within the Landfill. However, heat removal is known to be problematic in deep and wet waste masses in landfills. The Panel concluded these characteristics apply to the Landfill in which efficient release of heat is constrained by the quarry walls and geometry, resulting in excessive heat accumulation over time and the eventual development of ETLF conditions. A more detailed description of ETLFs is provided in Appendix D. Because hypotheses on the nature of subsurface reactions cannot be adequately addressed through existing site data, the discussion in Appendix D does not currently reflect a consensus opinion by all Panel members. However, the Panel was unanimous in the opinion that insufficient data limited any clear diagnosis pertaining to subsurface reactions.

The Panel agreed the Landfill is showing characteristics and early signs of developing into an ETLF. Fortunately, many of the engineering solutions for odor mitigation will also moderate this problem before ETLF conditions become difficult to control. However, the Panel concluded site data are insufficient to fully diagnose the degree to which the Landfill is evolving toward an ETLF including the speed of progression to ETLF conditions or the rate of migration within the Landfill. Therefore, the Panel recommended immediate development and rapid implementation of a data collection strategy to more fully address the ETLF diagnosis. Specific recommendations for an effective data strategy are provided in the next section of this report.

Findings:

1. Odors are believed to be primarily emanating from the Landfill/quarry sidewalls suggesting that the sidewall liner has been compromised. Odors are also likely emanating from the Landfill surface due to inadequate interim soil cover material.
2. Engineered measures to seal the sidewalls and mitigate the release of odors appear feasible. A site-specific design approach for sidewall emission reduction needs to be developed and tested before implementing site wide.
3. Air intrusion caused by insufficient daily cover use and operation of the landfill gas collection system appears to be resulting in non-ideal concentrations of O_2 in the waste mass.
4. The Landfill is exhibiting characteristics of an Elevated Temperature Landfill (ETLF), including low relative methane content in landfill gas, large and rapid settlements and the production of highly unusual odors. Left unabated, ETLF conditions will likely continue to develop over time.
5. There is insufficient data for diagnosing the state of ETLF conditions within the Landfill. A data monitoring program should be implemented concurrently with, and in a complementary manner to, the remedial strategy for controlling odors and the associated ETLF condition.

3.2. Landfill Settlement

Analysis of a series Landfill topographic surveys from June 2020 through November 2021 showed a net decrease in fill volume within the Landfill due to settlement even though waste was being received and added to the Landfill. As shown in **Figure 4**, the net decrease in Landfill volume from June 2021 to November 2021 was nearly 13,000 yd^3. Maps of the topographic surveys showed a pattern of decreased surface elevations in most parts of the southern and eastern areas of the Landfill and increased surface elevations in areas along the western edge of the Landfill where waste disposal operations were active. The Panel noted that a net settlement was most common in areas of the Landfill with no apparent waste disposal operations. The variable "apparent" or net fill rate is a function of the actual waste disposal rate and settlement within the underlying waste mass (i.e., if the waste mass settles faster than waste is placed, a net decrease in elevation will be apparent).

As a practical matter, settlement at the Landfill surface creates problems with operation of the landfill gas extraction wells. Information provided to the Panel indicates settlement has compromised a number of gas extraction wells, causing the wells to twist and shift horizontally and vertically. The result is that settlement likely contributes to oxygen intrusion and the inability of gas extraction wells to efficiently collect gases and dissipate heat within the Landfill.

Findings:

6. The Landfill is exhibiting differential spatial settlement with the greatest net settlement observed in areas where Landfill operations are minimal. The rate of settlement in 2021 is greater than settlement in the latter half of 2020, which suggests an acceleration in the rate of settlement. Settlement of this nature is characteristic of an ETLF.
7. Remedial actions will need to address anticipated settlement of the Landfill.

3.3. Landfill Leachate and Groundwater

Saturated conditions within the Landfill are the result of no on-site stormwater management and the ineffective transmission of water to the leachate collection system. Given that thick water-saturated waste is known to promote the development of ETLF conditions, the Panel concluded that additional engineered measures to effectively collect and remove stormwater from the landfill and to remove leachate from the Landfill are required to manage and prevent worsening ETLF conditions.

The Panel did not find sufficient evidence to suggest that increasing benzene concentrations over time in the gradient control and leachate samples were the result of an external source of contamination. Sustained benzene concentrations of 1.0 mg/L and greater in groundwater would require an external source (e.g., fuel spill) in close proximity to the Landfill. Available data indicates none of the monitoring wells in the vicinity of the Landfill show the presence of benzene. The Panel believes that benzene is likely being derived from the waste mass, indicating an internal source. However, the Panel did not have sufficient data to determine the mechanism of benzene production or release. Benzene is a compound common to leachate in ETLFs. In addition, self-sustaining subsurface exothermic reactions are known to produce benzene. The increase of benzene concentrations with time may be a useful indicator for identifying when ETLF conditions began developing in the Landfill.

The Panel did not reach a final consensus on the source of benzene in the gradient and leachate samples. Increasing benzene concentrations in the gradient water with time parallels a similar increase in benzene concentrations in leachate samples. The Panel observed that liquid removed from the leachate collection system appeared dilute and atypical of leachate present at other landfills. This further suggests a low rate of leachate collection from the Landfill through the collection system and mixing of the leachate with groundwater.

Findings:

8. Waste beneath the Landfill surface is saturated with leachate which is known to contribute to ETLF conditions including the generation of odors.
9. Prevention of additional infiltration of stormwater and removal of leachate from the waste mass to the extent practical must be addressed through engineered remedial actions.
10. Benzene is not believed to be derived from an external source of contamination based on currently available data. Benzene is likely being derived from the waste mass, but the mechanism of production or release is unknown due to insufficient data.

4. Summary of Recommendations

4.1. Odor Mitigation

The Panel reached consensus on a strategy for Landfill odor mitigation that consists of multiple engineered components. As previously stated, the recommended engineered remedial actions are intended to both minimize the release of odors from the Landfill, reduce Landfill temperatures, and manage problematic conditions thought to exist beneath the Landfill. This strategy includes preventing infiltration of rainfall and control and management of stormwater inside the Landfill.

This strategy may be best implemented in several stages. Any strategy will require engineering planning and design, contracting, and construction. Critical data gaps noted by the Panel are identified in this section of the report. An improved data collection strategy will lead to a clear diagnosis of subsurface conditions and reactions in Landfill and will facilitate performance assessment of a mitigation system and any proposed actions.

In addition, daily attention to the operation and maintenance of the gas extraction wells is absolutely necessary to success. This pertains to the existing system of gas extraction wells. This will require full-time staff adequately trained and devoted to oversight of the remedial system. Given the current supply chain concerns, spare pumps and related materials should be purchased and the inventory maintained by Landfill staff.

Recommendations for Odor Mitigation and Data Needs:

1. Test and construct a sidewall odor mitigation system around the Landfill perimeter that will be designed and constructed to mitigate landfill gases emanating from the Landfill/quarry sidewalls.
2. Improve the performance of existing gas extraction wells including minimizing air intrusion pathways through Landfill cover. Additional gas extraction wells will be needed to reduce emissions and temperatures.
3. Identify and eliminate to the extent practical any landfill gas fugitive emissions at the Landfill surface. Weekly monitoring activities of gas emissions at the Landfill surface will be required.
4. Install settlement plates and conduct monthly surveys to document the locations and rates of settlement in the waste mass.
5. Install and monitor a dedicated system of thermocouples in the waste mass to monitor Landfill temperatures for greater spatial resolution (horizontal and vertical) and to provide data at a greater frequency.
6. Install at least five (5) deep dedicated monitoring wells to enable sampling and characterization of leachate and measurement of temperature profiles in the waste.
7. Install and operate large-diameter dual-phase extraction wells for removal of gas and leachate. Treatment requirements for extracted leachate must be determined.
8. Install a temporary geosynthetic cover over the entire Landfill. This will require substantial grading of the existing Landfill surface to direct runoff to the southeast corner of the Landfill where it is expected a stormwater management pond can be constructed to manage stormwater that is collected on top of the geomembrane cover.
9. Develop and implement an effective and sustainable stormwater management plan and settlement management plan for the Landfill.
10. The Panel recommended an active community outreach program to communicate strategies, provide status and progress reports, and receive citizen feedback.

Recommendation 1 is a priority to fast-track odor mitigation. Recommendations 2 and 3 address data and monitoring gaps associated with emissions of odoriferous gases. Given the likelihood that the liner is breached along the sidewalls which allows landfill gas escape and discharged in chimneys to the atmosphere, the Panel recommended a gas collection system around the perimeter of the Landfill. One concept calls for pulling back the sidewall liner, installing a system of lateral gas collection pipes at the perimeter, and constructing a clay barrier to seal the perimeter. The Panel suggested a horizontal gas collection system installed at a relatively shallow depth will be more efficient at capturing odors than vertical gas wells.

The Panel recommended installation of a test system to assess the feasibility of any design. One challenge is the size and scope of the problem. Given the quarry perimeter is approximately 4,800 ft in length, the volume of fine-grain material needed to construct a clay/soil barrier will be substantial and will require a significant increase in truck traffic into and out of the quarry. Sources and supply of clay/soil should be addressed immediately. The Panel also discussed the installation of deeper vertical wells targeted near the Landfill perimeter to immediately address sideway emissions while the proposed lateral gas collection system is tested, designed, and constructed.

The Panel recommended investigating gas emissions passing through the Landfill cover to determine locations and extent of odor emissions emanating through the Landfill surface. The Panel recommended a careful evaluation to improve operational procedures. This includes addressing any air instruction caused by well over-drawing from the Landfill. The Panel also recommended supplementing the existing gas extraction well network with additional wells. An expanded the gas extraction system would target the interior of the Landfill and should be coordinated with the design of new dual-phase extraction wells.

Installation of settlement plates throughout the Landfill including in the general vicinity of existing gas extraction wells and the Landfill center is recommended as a first step to provide more frequently monitoring of settlement over time, particularly to identify areas of rapid settlement. The Panel recommended the use of drones or GPS survey of the Landfill surface on a monthly basis. Drones could also prove to be of value in the monitoring of Landfill surface emissions and temperature.

Data critical to this effort are devices to measure temperature above and within the water-saturated waste. The Panel discussed spacing of temperature sensors every 10-20 ft vertically through an array of boreholes covering the Landfill. This will enable continuous monitoring of Landfill temperatures and potential the rate of heat migration, delineation of hot stops of elevated temperatures and odor generation, and provide an effective means of monitoring performance of odor mitigation strategies. In addition, additional temperature data will be instrumental to directing additional remediation efforts to moderate subsurface reactions. **Recommendation 5 is a priority data need for tracking and controlling ETLF conditions.**

The Panel recommended installation of at least five (5) deep monitoring wells for sampling and characterizing leachate samples from the interior of the Landfill. These wells should include multi-screens at several depth for a clear understanding of spatial resolution of leachate quality. These data will be necessary for the design and operation of on-site water treatment which would serve as a pre-treatment step before discharge to the WWTP.

The Panel recommended installation of large-diameter (12-inch diameter) dual-phase extraction wells into the waste mass. The dual-phase wells are designed to extract of both gas and leachate. The aim of dual-phase extraction wells is to reduce temperatures in the Landfill and to remove leachate from the Landfill as a means to control and contain ETLF conditions. These wells would be spaced and located throughout the interior of the Landfill. Although the Panel discussed the technical details of these recommendations (e.g., use of sonic drilling techniques), the type and number of wells and their locations and specifications should be best determined by the City's engineering consultants.

The accumulation of water within the waste mass has likely promoted heat retention and elevated temperature conditions and reduces the effectiveness of the gas collection system. Removal of this water (leachate) is one strategy to removing heat. However, removal of liquids from the waste mass can be difficult. The characteristics of the extracted liquids will need to be tested to confirm the suitability for discharging the liquids to the wastewater treatment plant (WWTP), depending on the amount discharged, and these characteristics may cause violations of the Landfill Industrial Waste Water Discharge Permit issued by the regional WWTP. The recommended list of constituents necessary for characterization of the leachate is provided in Appendix E. Therefore, removal of leachate, extensive testing and possibly pretreatment will be needed to dispose of the leachate in an environmentally sound manner.

The Panel recommended installing an interim geosynthetic cover to provide a relatively impervious surface over the entire Landfill. This will significantly reduce the amount of precipitation infiltrating, reduce oxygen intrusion from the atmosphere, and also prevent uncontaminated runoff from contacting waste material in the Landfill. In order to place the interim geomembrane cover, careful preparation and shaping of the Landfill surface will be needed and continued maintenance of the interim cover will be needed to deal with settlement within the Landfill. Efficient runoff capture will require grading of the Landfill surface to direct the water to one or more stormwater retention basins to be located on top of the interim geomembrane cover. The Panel identified the southeast corner of the Landfill as the best location for a stormwater management pond based on the existing Landfill surface grades. Clean runoff water falling on the geomembrane would be captured and then be pumped out of the Landfill and discharged as uncontaminated stormwater to nearby drainage features.

The Panel contended that a well-designed and implemented stormwater management plan is needed to minimize the infiltration of stormwater into the waste mass. The management of stormwater within the quarry limits is critical to eliminating the current odor problem and preventing odors from forming in the future. It is also important to maintain the cleanliness of the storm water so that is can be directly discharged to nearby water bodies without additional treatment. The stormwater system should be designed to segregate and discharge clean water offsite (i.e., stormwater that has not contacted solid waste) from the contaminated water from the active disposal area. This requires continued maintenance of the interim geosynthetic liner, frequent testing of the storm water quality to ensure compliance with discharge regulations and maintenance of the stormwater management pond(s) and associated pumping system. The Panel assumed that the proposed stormwater management system can be operated under an existing discharge permit with potential modifications.

The Panel recognized that the recommendations related to odor emissions will not be an instant fix and that a number of steps are required to design, construct, and implement an effective solution. The Panel recommended the City develop and maintain an outreach program to engage citizens. This will be needed to adequate communicate plans and progress and to provide a means to receive input, feedback, and suggestion from the community.

4.2. Feasibility of Continued Operations

The Panel discussed the feasibility of the Landfill continuing waste disposal operations during implementation of an engineered remedial strategy to mitigate odors. The Panel divided into two breakout groups and discussed several options that would allow the City to continue accepting and disposing of waste in the Landfill. Each group then presented a summary of their discussions to the entire Panel. The two options discussed were (1) operating in a limited area of the Landfill while actions to mitigate odors were completed; and (2) installing an environmental hazardous waste dome (landfill cover) over the Landfill. The Panel also considered a variation of option (1) in which waste disposal operations continued during an interim period to shape the surface of the Landfill before constructing an interim geomembrane cover followed by early closure of the Landfill. The Panel discussed technical and economic issues and safety concerns with continued operations in the Landfill during construction of remedial systems and the possibility that disposal of waste would work cross-purposes with odor mitigation.

Recommendations for Continued Operations:

1. Continuing Landfill operations while implementing the proposed remedial actions is problematic. Limiting operations to the northern end of the Landfill while the ETLF condition in the southern area of the Landfill is addressed is not recommended.
2. The City should strongly consider a cessation of waste disposal operations at the Landfill due to incompatibility of operations with the necessary odor mitigation and ETLF remedial strategy. Short-term waste filling operations to shape the surface of the Landfill for the placement of the interim geomembrane cover must be carefully coordinated with engineers working on remedial actions.
3. The landfill dome option (or roof) is not recommended. A dome will be expensive, may not be resilient to major storms, and this concept does not have a sufficient track record for effective odor mitigation.

The Panel discussed the feasibility of limiting continuing operations in the northern end of the Landfill. Operations in the northern area are currently inactive and there appears to be adequate space for disposal of waste for the next 3 to 5 years. However, the Panel concluded the disadvantages of this approach greatly outweigh the positives. Operating in the north end of the Landfill would prevent the implementation of most components of the odor mitigation strategy. In particular, this would preclude the use of a geosynthetic cover in this area, which would allow infiltration of precipitation and oxygen into the Landfill. Panel members noted that while the temperature in the northern end appears under control, this may not be the case with time. Any increases in landfill gas temperatures above 55°C (131°F) may necessitate a temporary or permanent cessation of operations in the northern area. Contributing factors include the cost of expanding the sidewall liner system in the north end of the Landfill (approximately $4M).

The Panel also raised significant concern for worker safety given projected construction of the mitigation system including additional equipment and truck traffic entering and exiting the Landfill. In addition, the installation and operation of the data collection system alone is incompatible with continuing operation in the Landfill. In summary, the Panel concluded that projected remedial work at the Landfill will conflict with continuing operations.

The Panel was intrigued by the concept of covering the entire open area of the Landfill with a roof. This concept has been used at other landfills and hazardous waste sites but on a smaller scale. A closed roof system would consist of a frame, synthetic roofing, and a ventilation system designed to capture and remove odors and prevent infiltration of precipitation. The advantages for application to the Landfill is the elimination of rainfall and the potential for odor mitigation. The primary disadvantage is a landfill roof approach does not directly address the source of odors and ETLF concerns. Additional resources would be required to mitigate Landfill temperatures. The Panel noted disadvantages to this approach including cost considerations, unproven deployment of such an approach on a similar scale, and the potential for damage to the structure from high-intensity storms. The roof would require an additional stormwater management system external to the Landfill and within the facility.

The Panel recommended the City create a plan to modify near-term Landfill operations in conjunction with odor mitigation strategies. The City should work with engineers on a strategy to optimize waste disposal for shaping of the Landfill surface and protecting worker safety as mitigation actions ramp up. The Panel recommended the City should strongly consider a cessation of operations at the Landfill once the shaping activities are completed due to incompatibility of the waste disposal activities with the recommended odor mitigation and ETLF control strategy. Not knowing the feasibility of when operations could resume and the scale and duration of future waste disposal, the City is advised to begin exploring alternative disposal options for municipal solid waste.

4.3. Options for Early Closure

The Panel discussed options for early closure for the Landfill. The feasibility of several options considered the Panel included (1) installation of a permanent landfill cap at the current waste level and following mitigation of odors and reduction of landfill temperatures; and (2) rapid fill of waste (approximately 4,000,000 yd^3) to the design level (i.e., top of the quarry) followed by installation of permanent landfill cap. The Panel considered this latter option under the scenario of resuming operations after actions to mitigate odors and reduce landfill temperatures were completed. The Panel also considered the feasibility of lowering the quarry walls with the goal of reducing the volume of waste material required to fill the Landfill to a sustainable grade condition for post-closure care and accelerate time to completion. The Panel discussed these questions in breakout sessions, and each group reported back to the entire Panel.

Recommendations for Landfill Closure:

1. Installing a permanent landfill cap designed to accommodate expected waste mass settlement without additional disposal of waste (other than shaping the Landfill surface) once odors and landfill temperatures are adequately reduced is a feasible option.
2. Rapid fill of the remaining permitted air space in the Landfill followed by a permanent landfill cap is not recommended given concerns for the ETLF considerations and cost considerations.
3. Resuming operations at the Landfill in the future may be technically feasible once the odors are controlled and ETLF conditions managed. However, there may be other technical, cost, and political considerations that would inform such a decision.

The Panel concluded that a final cover can be constructed over the landfill at the current level of waste. The final cover system may vary from the current permitted design configuration depending on the findings of future engineering analyses. The design will need to include considerations for stormwater management, gas collection and control, settlement, and site monitoring. If the final cover design varies from the currently permitted configuration, the DEQ would need to review and approve. Stormwater management will remain an issue. The cap should be designed to match the proposed reshaped topography of the Landfill surface to leverage the existing stormwater infrastructure. The final design will require approval and a permit by the DEQ since it is expected to differ from the currently permit.

The Panel identified numerous technical challenges and costs associated with filling the quarry to the rim. The sidewall liner system would be expensive to complete, and evidence suggests there are flaws in the existing system so continuing liner system design is not advisable. The Panel discussed the use of fine-grained soil for building a sidewall barrier as an alternative to the liner system, but material cost and supply may be problematic. The Panel discussed the feasibility of increasing the rate of fill to 1,600 yd^3 per day from the current disposal rate of 500 yd^3 per day as a means to accelerate time to completion but questioned the feasibility of receiving and handling this volume of waste in such a small disposal area. The concept of lowering the quarry walls was viewed as expensive and risky, and is not recommended.

The Panel considered resumption of operations following mitigation of odors and reduction and management of landfill temperatures as potentially feasible. However, the cost to create a barrier along the Landfill sidewalls and the likelihood of a long-term need for the odor mitigation and landfill temperature control system are just two factors that prevent a clear definitive response to this question.

5. Additional Recommendations

The Panel concluded capturing odors near surface while feasible is not the only critical concern. Elevated temperatures within the Landfill appears to be a major source of the odors and must be addressed to avoid long-term persistence. The Panel consensus was that the Landfill is exhibiting early signs of an ETLF which is linked to production and release of odors. This condition has the potential to worsen and must be carefully managed. Monitoring and data collection will be a critical element to guide future steps, and data-driven adaptive strategies are required. Defining success and documenting the efficacy of the remedial measure with this data will be necessary to convince the community that the proposed solution is effective and permanent.

The Panel recommended that DEQ consider a role for the Panel in the short term and beyond. Members of the Panel expressed a willingness to reconvene to receive updates on engineering actions, consider data and findings, and for the Panel to provide recommendations to the City and DEQ on next steps.

The closure of this Landfill will be a long-term project. The buried waste will require several decades to stabilize, and failure to properly control stormwater and account for waste settlement has the potential to reinitiate the elevated temperature conditions, along with the associated odors and production of gases containing hazardous substances such as benzene. Therefore, the development of a long-term plan to monitor Landfill conditions, to repair and replace equipment, construct a Landfill cap, and maintain the gas and leachate collection systems is critical. Therefore, a provision for a secure and appropriate level of funding, including technical and operational resources for long-term management of the Landfill is necessary.

Finally, the Panel emphasized concern for the design, operation, and maintenance of water control and management systems at the Landfill which are integral to successful outcomes. Stormwater control is vital to the success of the proposed remedial approach for odor mitigation and the control of Landfill temperatures and intrusion of oxygen. The volume of stormwater runoff from an impermeable geomembrane will be substantial and the time of concentration will be very minimal. Both groundwater and stormwater will need to be managed forever. Operating and maintaining a system for the removal of groundwater and stormwater in a deep quarry containing a closed landfill will be a major challenge. This will require a plan for operating and maintaining these systems for decades into the future and the required funds for effective compliance. Permanence and sustainability in systems to hydraulically control and convey water cannot be over emphasized.

6. References (see Appendix D for additional references)

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Figures

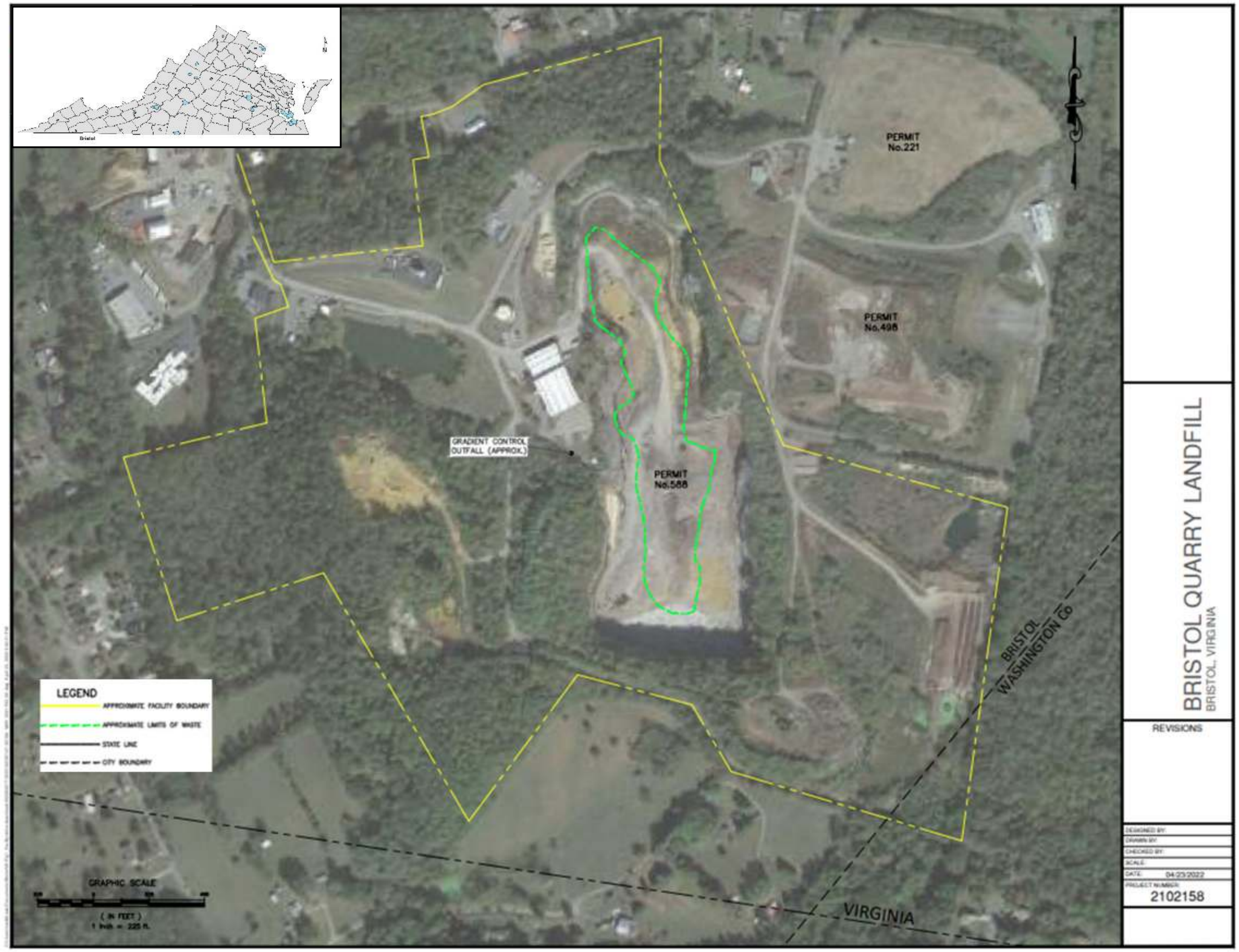

Figure 1. Plan view of Bristol Integrated Solid Waste Management Facility which includes the Bristol Quarry Landfill (Permit 588) and adjacent landfills (Permit 221 and Permit 498). Drawing modified from Draper Aden Associates.

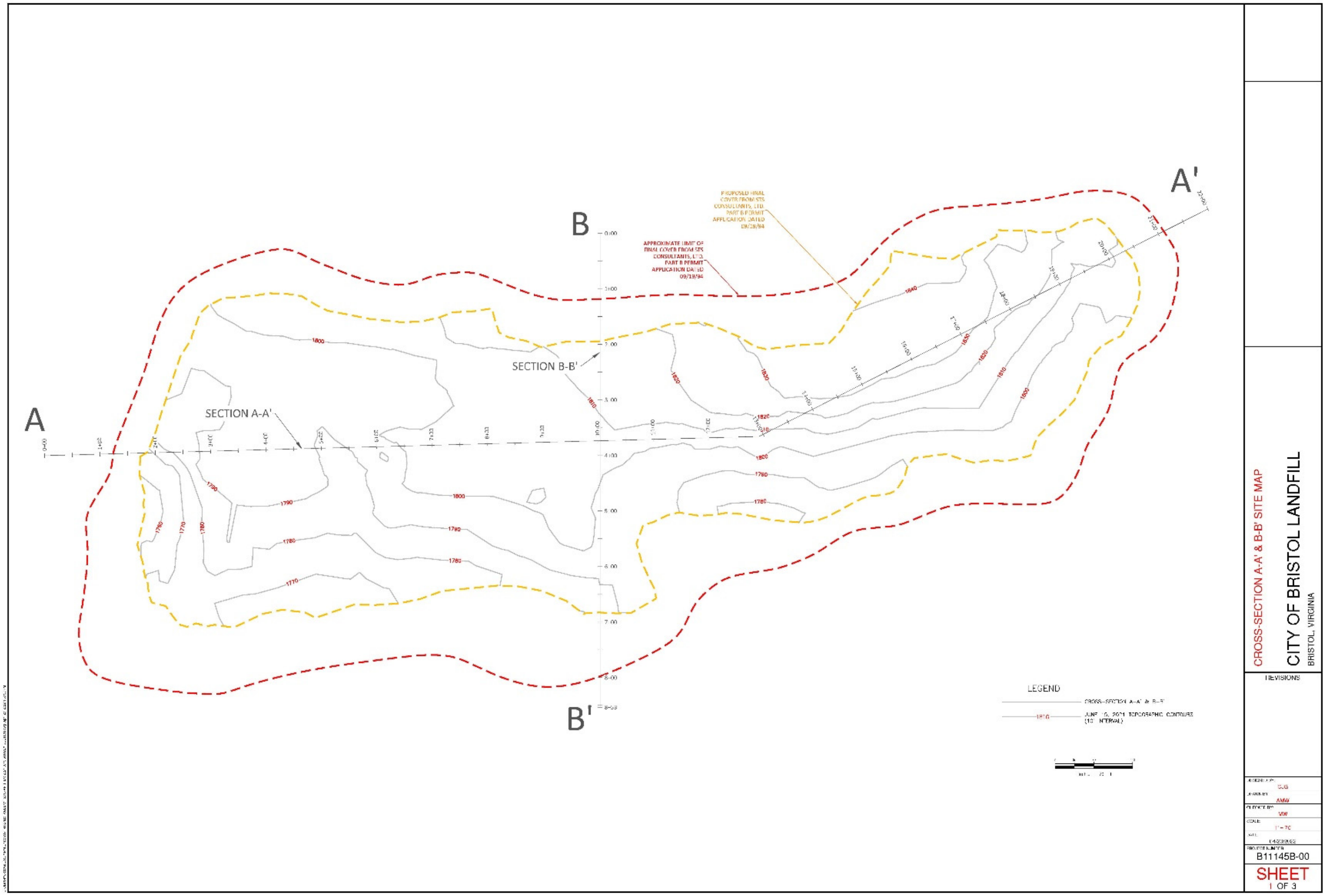

Figure 2. Plan view of Bristol Quarry Landfill with 2021 topographic contours of the landfill surface (Draper Aden Associates) and location of cross sections A-A' and B-B'. Drawing modified from Draper Aden Associates.

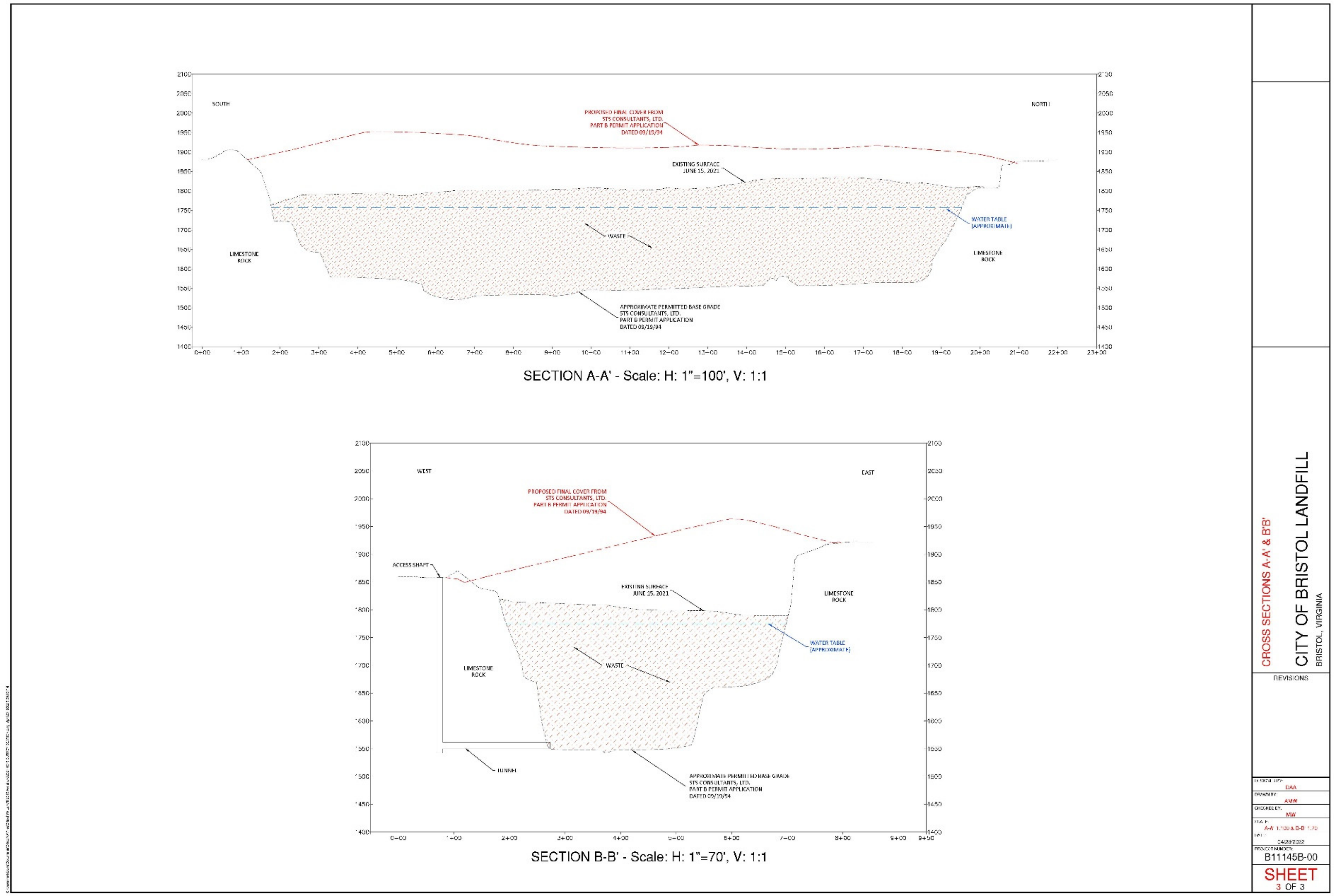

Figure 3. Vertical cross sections through three sections of the Landfill (refer to Figure 1 for locations).

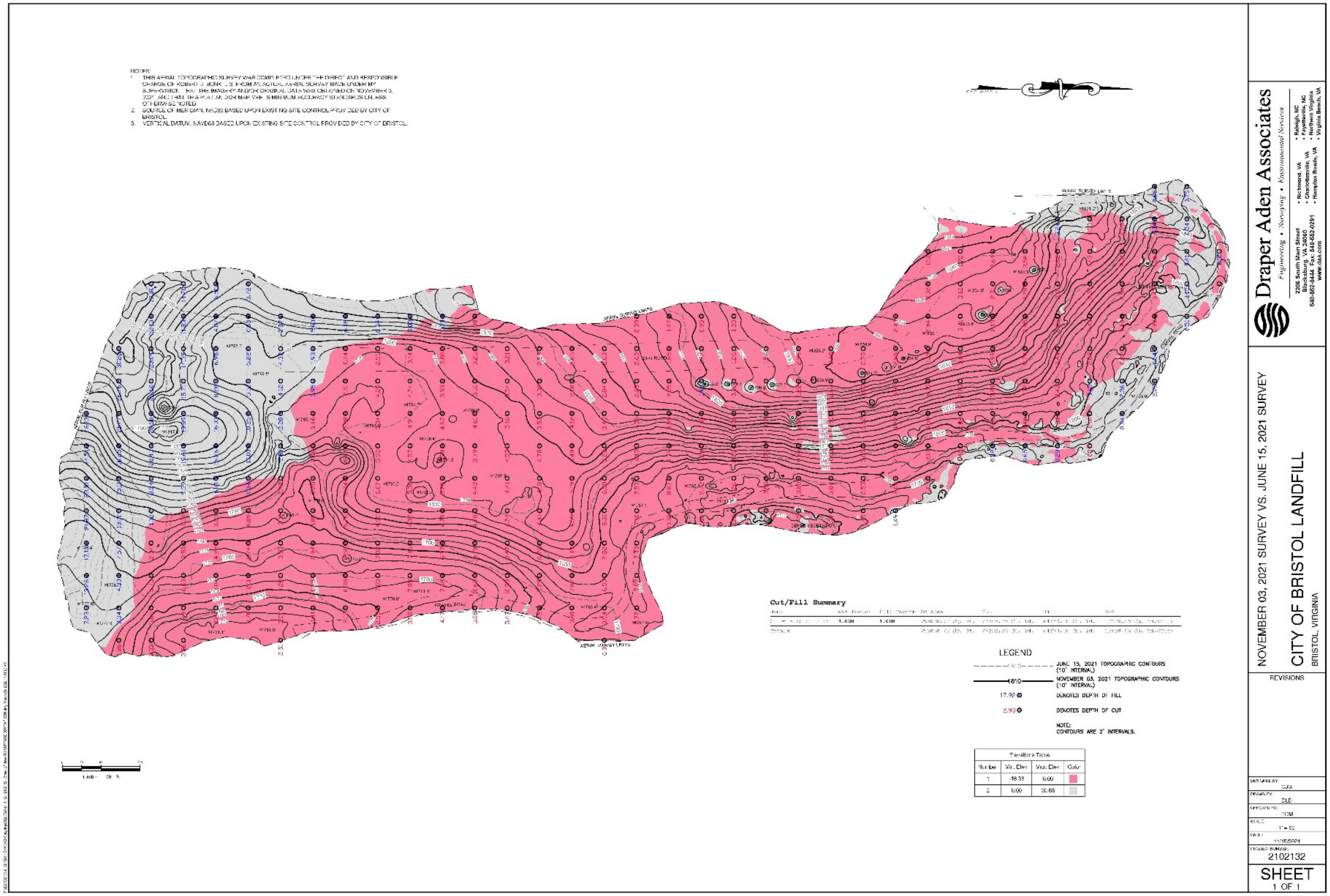

Figure 4. Depiction of Landfill net settlement based on differences in surface survey data collected in June 2021 and November 2021. The red-shared areas show areas of net decrease in the Landfill surface between the two surveys. (Draper Aden Associates)

Appendices

Appendix A

Bristol Landfill Expert Panel – Biographical Sketches

Expert Panel Member	Affiliation
Craig H. Benson, PhD, PE, DGE, BCEE, NAE	University of Virginia
Eric D. Chiado, P.E.,	Civil & Environmental Consultants, Inc.
Robert B. Gardner, P.E., BCEE	SCS Engineers
John T. Novak, Ph.D., P.E.	Virginia Tech
Tony Sperling, P.Eng., Ph.D.	Sperling Hansen Associates
Timothy D. Stark, Ph.D.	University of Illinois at Urbana-Champaign
Todd Thalhamer, P.E.	Hammer Consulting Services
Mark A. Widdowson, Ph.D., P.E. (Chair)	Virginia Tech
Michael G. Williams, CPG	WSP Golder
Eddie Wyatt	Carlson Environmental Consultants

Biographical information of the Expert Panel Members is available at the DEQ website

www.deq.virginia.gov/get-involved/topics-of-interest/bristol-landfill

Appendix B

Bristol Landfill Expert Panel - AGENDA

Sunday, March 20

7:00-9:00 pm. Dinner and Presentation (Overview of Bristol Landfill)

Monday, March 21

7:00-8:00 am. Breakfast

8:00-8:30 am. Introductions; Agenda, Schedule, and Logistics; Meeting Objectives

8:30-9:45 am. Continuation of Bristol Landfill Overview (Ernie Hoch, DAA)

9:45-10:00 am. Break

10:00 am-12:00 pm. Landfill Tour

12:15-1:15 pm. Lunch

1:15-1:30 pm. Post-Tour Follow-up (Ernie Hoch, DAA)

1:30-3:00 pm. Presentations and Discussion

- **Exothermic Reactions – Dr. Craig Benson**
- **Odor Mitigation/Landfill Closure – Dr. Tony Sperling**

3:00-3:15 pm. Break

3:15-5:45 pm. Break-Out Groups/Summary

5:45 pm. Adjourn for the day

6:30-8:00 pm. Dinner and Discussion

Tuesday, March 22

7:00-8:00 am. Breakfast

8:00-9:30 am. Agenda and Schedule; Open Discussion – Day 1 Follow-Up

9:30-9:45 am. Break

9:45-11:45 am. Working Session/Morning Summary

12:00-1:00 pm. Lunch

1:00-2:45 pm. Working Session/Afternoon Summary

2:45-3:00 pm. Break

3:00-4:30 pm. Panel Summary

4:30 pm. Adjourn for the day

6:00-8:00 pm. Dinner

Appendix C

Email summary from the Panel Chair to DEQ

VIRGINIA TECH. Mark Widdowson <mwiddows@vt.edu>

Bristol Landfill Expert Panel - Summary of recommendations

Mark Widdowson <mwiddows@vt.edu> Mon, Mar 28, 2022 at 8:00 AM
To: "Rolband, Michael" <michael.rolband@deq.virginia.gov>
Cc: Craig Benson <chbenson@chbenson.org>, Eddie Wyatt <mwyatt@cecenv.com>, Eric Chiado <echiado@cecinc.com>, "Krause, Max" <krause.max@epa.gov>, Mark Widdowson <mwiddows@vt.edu>, Mike Williams <Michael_Williams@golder.com>, "Novak, John" <jtnov@vt.edu>, Robert Gardner <BGardner@scsengineers.com>, Timothy Stark <tstark@illinois.edu>, Todd Thalhamer <ltfire88@gmail.com>, Tony Sperling <sperling@sperlinghansen.com>, "Randall C. Eads" <CityManager@bristolva.org>, Lindsey Paisley <lindsey.paisley@deq.virginia.gov>

To: Michael Rolband, Director, Virginia Department of Environmental Quality

From: Mark A. Widdowson, Chair, Bristol Landfill Expert Panel

Date: March 28, 2022

The expert panel appointed by the Commonwealth to address persistent odors from the City's landfill has identified and will be recommending effective strategies to mitigate landfill odors. The Panel's recommendations will include steps for immediate emissions containment. These steps will be deployed within the landfill and analyzed to confirm their effectiveness. The Panel is recommending additional engineering design, construction, and operational steps for managing the landfill in an environmentally responsible manner now and into the future. The details of the Panel's findings and recommendations will be provided to you in a report on or about April 25th.

cc: Bristol Landfill Expert Panel Members, City of Bristol

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Appendix D

REACTION MECHANISMS AND HEAT TRANSFER IN ELEVATED TEMPERATURE LANDFILLS

By Craig H. Benson

Elevated temperature landfills (ETLFs) are landfills for which waste temperatures are in excess of 55 ^{o}C over a broad area for a sustained period. They differ from landfills that have a "hot well" (or a few hot wells), which are common throughout the US, or landfills experiencing a surface fire (Barlaz et al. 2021). ETLFs are relatively uncommon, with only about a dozen ETLFs known to exist in North America. ETLFs generally exhibit waste temperatures substantially in excess of 55 ^{o}C that are associated with a heat source deep within the waste mass. ETLFs exhibit high leachate generation rates; strong leachate with high biological oxygen demand (BOD), high chemical oxygen demand (COD), and concentrations of organic compounds an order of magnitude above typical leachates; landfill gas with low primary gas ratio (CH_4/CO_2) along with CO and H_2; large and rapid settlements; and strong odors (Barlaz et al. 2016, 2021; Benson et al. 2017). These conditions have the propensity to compromise control and containment systems, preclude conventional leachate treatment processes, and disturb neighboring communities. Managing ETLFs has been very costly in some cases.

The first three ETLFs in the US were encountered between 2005 and 2010. They were deep landfills that were very wet. Leachate levels at two of the landfills were in excess of 60 m above the base of the landfill. The other landfill had saturated waste at depth from extensive leachate recirculation. One of the landfills had records indicating acceptance of industrial wastes that could be responsible for heat-generating reactions, whereas the other two had no such records. At all three landfills, the zone of heat accumulation was deep and expanded over time, creating concern that an unknown reaction that could not be controlled was propagating deep within the landfill. The highly unusual and odiferous gas at these ETLFs, described by some as "reaction gas," reinforced the unique reaction hypothesis (*aka* as subsurface exothermic event, or SSE).

Nothing like this had been experienced before in the solid waste industry, which caused grave concern and was considered to be an "existential threat" to the viability of the industry. This concern led to a detailed study of ETLFs by Barlaz et al. (2021) under the sponsorship of the Environmental Research and Education Foundation (EREF). Findings from this study are the primary basis of the content described herein.

Early Hypotheses

The presence of aluminum processing waste at one of the three early ETLFs led some to infer that exothermic reactions associated with corrosion of aluminum dross, exacerbated by leachate recirculation that would promote aluminum corrosion, was the source of the excessive heat. However, analysis of the recirculation data for this ETLF along with disposal records demonstrated that dross disposal and leachate recirculation were conducted predominantly in different areas of the landfill, and that that the recirculation area was coincident with portions of the landfill where large volumes of highly reactive baghouse dust were disposed. A follow-on study conducted by USEPA (Huang et al. 2011) showed that corrosion of aluminum dross generated temperatures far different than observed in the field. Thus, the causative mechanisms at the first ETLF were unclear. No aluminum process wastes or other special wastes known to generate heat were found in an exhaustive review of waste receipts at the other two ETLFs, and no causative mechanisms for the elevated temperatures be determined.

Two competing reaction hypotheses were proposed to explain the heat and elevated temperatures at these three landfills: propagating fronts associated with smoldering combustion (by Jafari et al. 2017) and exothermic pyrolysis (by Barlaz et al 2017a, Tupsakhare et al. 2020). Smoldering is slow and flameless combustion sustained by the heat associated with oxidation of the surface of a condensed-phase fuel (Ohlemiller 2002, Ciuta et al. 2014, Rein 2016). Smoldering was considered viable because CO is encountered in gas at ETLFs, oxygen is constrained in MSW landfills (particularly at depth), and some wastes exhumed from ETLFs have a black appearance that resembles char. Elevated temperatures at these ETLFs appeared to be migrating, and smoldering often generates gases with a strong organic odor, conditions consistent with ETLFs. However, smoke and soot, common byproducts of smoldering, have not been observed in ETLFs and saturated conditions in ETLFs make transport of oxygen to a reacting surface negligible. Exothermic pyrolysis was considered viable, as pyrolysis of biomass can be exothermic under conditions of elevated fluid pressure (Antal and Gronli 2003), is known to produce CO and H_2 as observed in ETLFs, and has been shown to create the same black appearance resembling char observed in MSW in ETLFs (Barlaz et al. 2016b, Tupsakhare et al. 2020). Exothermic pyrolysis also softens biomass, which is consistent with accelerated compression and settlement, and releases free liquids that become leachate. The decomposition processes in pyrolysis also create transformation intermediates that have similar attributes as the leachate found in ETLFs. However, exothermic pyrolysis had heretofore not been observed in MSW landfills.

Sufficient evidence to confirm the smoldering and exothermic pyrolysis hypotheses was never obtained, and evidence to the contrary is abundant. For example, smoldering of organic matter inundated under 10s of meters of water or in saturated waste, conditions predominant in ETLFs, is thermodynamically impossible. In addition, while temperatures are elevated in ETLFs, temperatures consistent with smoldering or combustion (> 250 °C) have not been encountered. The highest recorded temperatures in ETLFs are approximately 150 °C, with most not exceeding 120 °C. Exothermic pyrolysis is theoretically possible, but experiments demonstrated that the energy produced by exothermic pyrolysis of MSW is far too small at the fluid pressures found in ETLFs to have any substantive impact on temperatures within a landfill (Tupsakhare et al. 2020, Barlaz et al. 2021). Consequently, both hypotheses have been abandoned by the landfill industry.

Constrained Heat Transfer Hypothesis

As more ETLFs were encountered and studied by the ETLF team, several common attributes were evident. ETLFs had a very thick waste mass and were very wet, often from leachate recirculation intended to simulate biodegradation, enhance gas production, and promote waste stability. Removing gas and leachate from the waste mass was difficult, precluding efficient heat removal and compounding difficulty in managing odors. These observations led to the hypothesis that poor heat transfer combined with heat-generating wastes, rather than a unique initiating and propagating reaction, was primarily responsible for ETLFs. Heat removal by convection is compromised in deep and wet waste, and diffusive heat transfer is highly constrained when heat-removing boundaries are far from the heat source (e.g., atmosphere above and earth below). In effect, the constrained heat transfer hypothesis states that ETLFs occur when heat is generated at a faster rate by reactions in the waste than can be dissipated by heat transfer mechanisms.

Under the constrained heat transfer hypothesis, any and all exothermic reactions in waste have the propensity to contribute to heat accumulation that could lead to an ETLF. A variety of abiotic and biotic mechanisms can generate heat in municipal solid waste (MSW) landfills and potentially could contribute to an ETLF under conditions of constrained heat transfer. The most common biotic mechanism is anerobic decomposition of organic matter, which is responsible for temperatures on the order of 45-55 ^{o}C commonly encountered in MSW landfills that are operating normally (Barlaz et al. 2017a, Hao et al. 2017). Aerobic microbial degradation of organic matter can also be a significant source of heat in landfills, and is frequently responsible for MSW “landfill fires” under circumstances that are thermodynamically favorable (Hao et al. 2017). Abiotic reactions associated with corrosion of metals and hydration and carbonation of ashes can be exothermic, and can be responsible for heat generation and accumulation in landfills (Barlaz et al. 2017b). Each is described briefly below.

Aerobic reactions. Aerobic degradation can occur though different oxidation reactions, such as methane oxidation (by methanotrophs) or cellulose oxidation. Both of these reactions are highly energetic, with heat release on the order of 15-30 MJ/kg-reactant (Hao et al. 2017). However, the propensity of these aerobic reactions to generate heat is controlled by the availability of oxygen, which is nearly absent at depth in very wet landfills.

Anaerobic reactions. Anaerobic degradation of cellulose, hemicellulose, and starch are less energetic, with heat release on the order of 1-2 MJ/kg-reactant, but are common in MSW in the absence of oxygen, and occur at depth in very wet landfills (Hao et al. 2017).

Metal corrosion reactions. Iron and aluminum metal are common in landfills and can corrode at depth in the absence of oxygen in wet landfills. Anerobic iron corrosion releases 1.2 MJ/kg-Fe and corrosion of aluminum releases 16 MJ/kg-Al (Hao et al. 2017).

Ash hydration and carbonation reactions. Ashes disposed in landfills release heat through hydration reactions with oxides and carbonation reactions with hydroxides. The heat released by hydration reactions is common in many environments (e.g., hydration of fly ash used in concrete). Carbonation reactions are less significant in many applications, but can be appreciable in MSW because of the preponderance of CO_2 as a reactant. Hydration reactions release on the order of 1 MJ/kg-reactant, and carbonation reactions on the order of 2 MJ/kg-reactant (Hao et al. 2017).

Heat Accumulation from Reactions

Hao et al. (2017) used a batch reactor model to evaluate the potential for each of the aforementioned reaction mechanisms to contribute to an ETLF. The model considered ingress of water via percolation into the waste (for corrosion) and egress of heat via landfill gas (convection), leachate drainage (convection), and heat loss from the boundaries. Simulations were conducted with and without heat loss at the boundary, the latter simulating the constrained transfer of heat expected in a deep and wet landfill. Anerobic degradation reactions included a release reduction factor to account for diminished microbial activity at temperatures exceeding 55 °C. Hao et al. (2020) extended these concepts to a geometrically realistic scenario representing a landfill using a finite element model simulating heat generation and heat transfer though diffusion and convection mechanisms.

Hao et al. (2017, 2020) demonstrate that the classic "belly curve" for waste temperature (Fig. 1, peak temperature at depth with heat loss towards the atmosphere and to the earth) found in ETLFs should be expected in deep MSW landfills, with temperatures being higher for conditions that constrain heat dissipation and for waste with greater propensity to generate heat. They demonstrate that a landfill with MSW alone can become an ETLF if heat transfer and removal is highly constrained, with the peak temperature at depth exacerbated as the waste thickness increases. Higher temperatures are realized when wastes generating heat by abiotic reactions are added to the waste mass.

Hao et al. (2020) demonstrate that adding modest amounts of ash (10-20% by mass) can result in peak temperatures at depth in excess 55 °C, and as high as 110 °C within 30 years of disposal (Fig. 2). Hao et al. (2020) show that focused disposal of ash (not mixed with MSW) can result in even higher temperatures that are localized. Similar outcomes are expected for other heat-generating wastes.

Waste temperatures in excess of 100 °C exist in the south end of Bristol Landfill, where a thick layer of ash was placed near the base. An example of what appears to be ash stockpiled near the base of the south area is shown in Fig. 3a. Ash was also mixed with the MSW, as shown by the pile in the waste shown in Fig 3b. Hydration and carbonation of this ash in the south end is a likely cause of the elevated temperatures in Bristol Landfill. The deep and wet waste in the south end constrains heat transfer, allowing heat to accumulate and causing temperatures to be elevated.

Practical Implications

Hao et al. (2017, 2020) demonstrate that the primary cause of ETLFs is the inability to release heat from deep and wet waste at a rate that is faster than the heat-generation rate associated within the waste mass. This occurs without a unique and heretofore unencountered exothermic reaction in MSW (smoldering, exothermic pyrolysis) or unusual reaction mechanisms, fronts, or pathways.

Accordingly, ETLFs are managed (and prevented) by removing the heat as effectively and efficiently as possible through landfill infrastructure, such as leachate and gas removal systems. This is one of the primary reasons why landfill operators have moved to large-diameter caisson wells built from the floor of the landfill upward during operations. These wells promote effective gas extraction and landfill drainage, allowing the gas and liquids to be efficiently removed along with the heat embodied within the fluids. This approach has been extremely effective in practice over the past 5 years.

The landfill engineering practitioner is left with the question – why ETLFs now and not 30 years ago? The answer is in the evolution of landfill engineering practice over the last three decades, since the advent of RCRA Subtitle D. During this period, large landfills became predominant with deep waste commonplace (100 m thick or more in some cases). Leachate recirculation and bioreactor landfills also became prominent in the period between 2000-2010 as a means to promote waste decomposition and stabilization along with greater gas generation for renewable energy applications. These changes in practice led to deep and oftentimes very wet landfills, conditions that constrain heat dissipation and lead to ETLFs.

The unintended consequences of these landfill management strategies led to substantial changes in landfill practice over the past five years, including limited (or no) leachate recirculation, an emphasis on internal drainage, and implementation of gas collection infrastructure from the bottom up. These changes in practice have ameliorated the deep and wet condition and have substantially improved heat removal, greatly reducing the likelihood that ETLFs will occur in modern landfills in the future.

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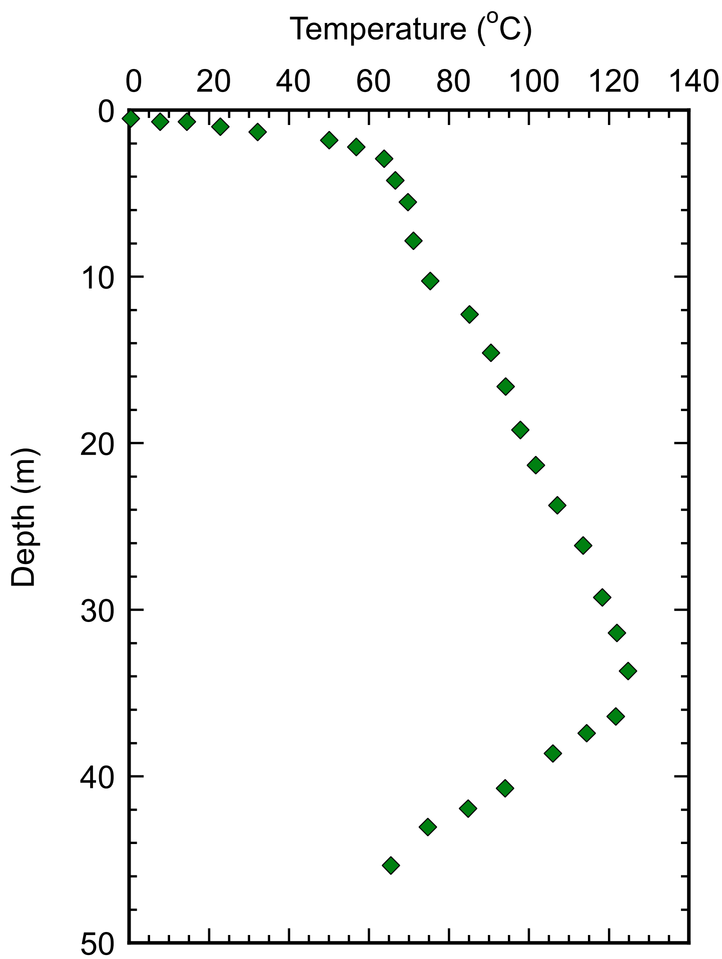

Fig. 1. Typical "belly curve" of waste temperatures encountered in ETLFs with heat source more than 30 m (100 ft) below ground surface.

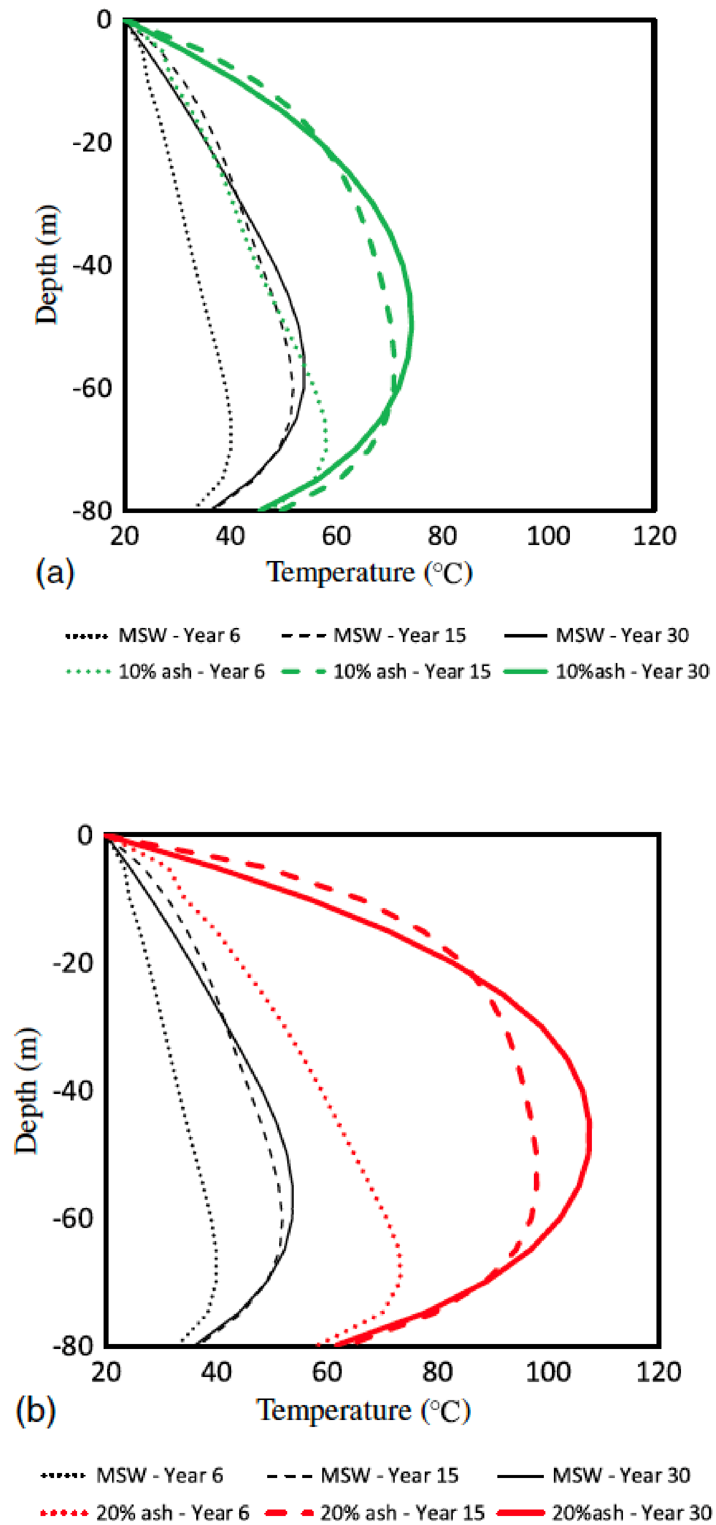

Fig. 2. Temperature profiles reported by Hao et al. (2020) for 80-m-deep MSW blended with 10% (a) and 20% ash (b).

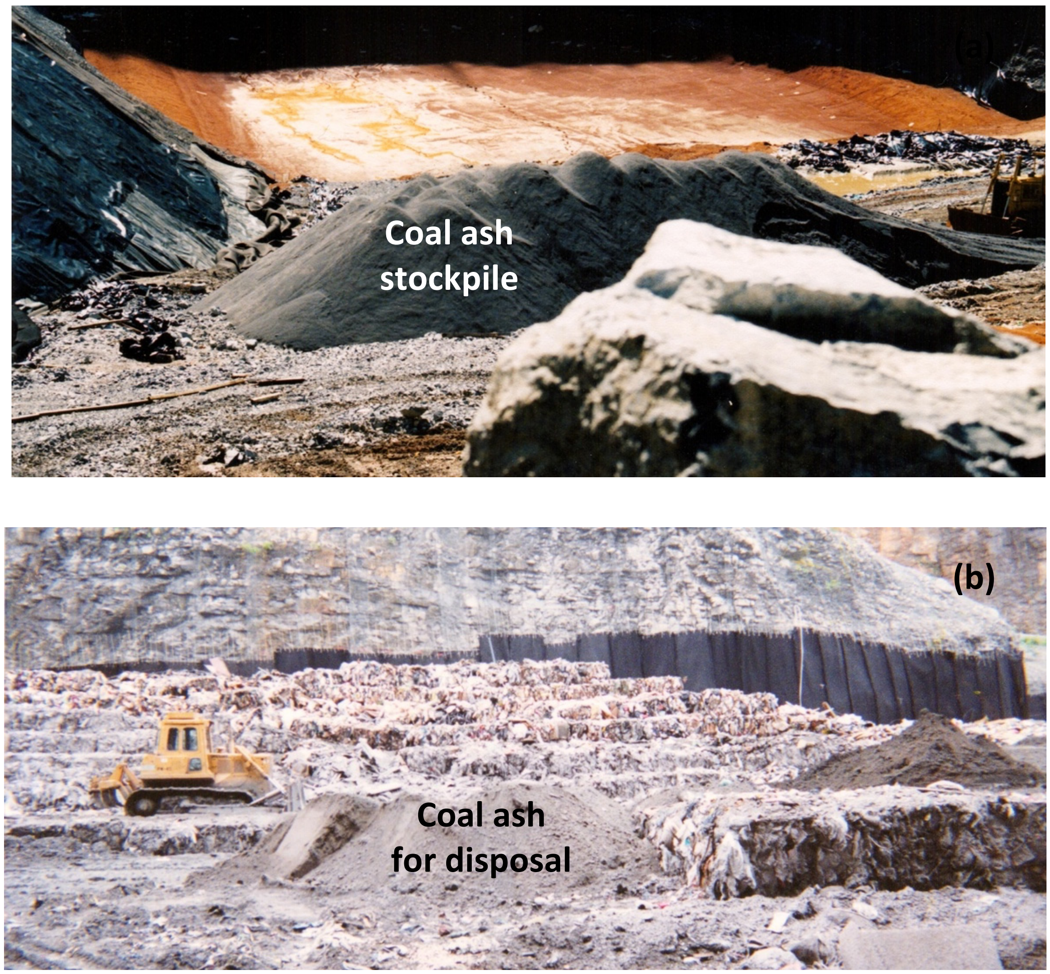

Fig. 3. Coal ash stockpiled near base of south end of Bristol Landfill ca. 2000 (a) and ash pile to be added to waste mass ca. 2004 (b).

Appendix E

Recommended Leachate Testing

Constituent
Chemical Oxygen Demand (COD)
Biological Oxygen Demand (BOD)
Volatile Fatty Acids
pH, eH, conductivity
Ammonia
Total Kjeldahl Nitrogen (TKN)
Toxicity testing for nitirficaiton
Acetone
MEK
Phenols
Anthracene
BTEX compounds
Benzene
Toluene
Ethylbenzene
Xylenes
Metals
Tetrahydrofuran

Appendix F

CAUSES OF ELEVATED TEMPERATURES IN MUNICIPAL SOLID WASTE LANDFILLS

By Timothy D. Stark, PhD, P.E. and Todd Thalhamer, P.E.

INTRODUCTION

Elevated temperature landfill events (ETLEs) have been documented in municipal solid waste landfills (MSWLFs), construction demolition debris landfills, industrial waste fills, and sanitary dumps (Martin et al. 2013; Øygard et al., 2005; Sperling and Henderson 2001; Ettala et al. 1996; Frid et al. 2010). Approximately 840 unique elevated landfill temperature incidents occurred annually in the U.S. from 2004 to 2010, where more than 25% are repeat incidents at a specific site (Powell et al., 2016). The frequency of occurrence at a given site supports observations that elevated landfill temperatures are difficult to fully extinguish, thus presenting a significant threat to the environment by emitting pungent odors (reduced sulfur compounds and organic acids), volatile organic compounds, **benzene**, which has also been detected at the Bristol, Virginia MSWLF, and particulate matter (Nammari et al., 2004; Ruokojarvi et al., 1995; Lonnermark et al., 2008; Chrysikou et al., 2008). In general, gas concentrations of non-methane organic compounds (NMOCs) from MSW/Subtitle D landfills double with every 18^0F (10^0C) of temperature increase (ATSDR 2001). Some NMOCs are known or suspected carcinogens and are classified as hazardous air pollutants (HAPs). Benzene and methyl-ethyl ketone are the two compounds consistently found at elevated levels during landfill elevated temperature investigations. In addition, ETLEs can impact the integrity of the bottom, cover, and side geosynthetic liner systems, also experienced at Bristol, VA MSWLF, degrade leachate quality and gas composition, induce slope instability, and result in excessive and rapid settlements (Lewicki, 1999; Jafari et al., 2014; Stark et al., 2012; Øygard et al., 2005).

Based on prior ETLEs in MSWLFs, Jafari et al. (2017) propose the following landfill classification framework to define spatial boundaries of internal processes occurring during an ETLE. If these boundaries or conditions occur over a significant area, i.e., in multiple gas extraction wells for a sustained period, the relevant classification should be applied and corresponding remedial measures implemented (Stark and Jafari, 2017). For example, if the parameters for the gas front are detected over a landfill filling area or cell, it should be assumed that the gas front is present in this area and subsequent classifications, e.g., temperature front and/or smoldering front, may appear or arrive in this area in the near future. The landfill classification system by Jafari et al. (2017) consists of the following sequence and criteria:

1. **Normal behavior or Anaerobic Decomposition:** Gas temperatures are below 131^0F (55^0C) and ratio of methane (CH_4) to carbon dioxide (CO_2) flow rate is near or greater than unity (1.0).

2. **Gas Front:** Decreasing ratio of CH_4 to CO_2 flow rates and gas wellhead temperatures at or above the New Source Performance Standards (NSPS) threshold of 131^0F (55^0C).

3. **Temperature Front:** Increasing gas wellhead temperatures above 131^0F (55^0C) and decreasing ratio of CH_4 to CO_2 flow rates.

4. **Smoldering Front:** The smoldering front includes carbon monoxide (CO) concentrations greater than 1500 ppmv, ratio of CH_4 to CO_2 flow rates less than 0.2, and gas wellhead temperatures greater than 149^0F (65^0C), i.e., waste temperatures greater than 176^0F (80^0C). The tail of the smoldering front can be delineated by settlement strain rates of greater than 3%/year, which signifies thermal degradation or consumption of the waste is occurring.

The zones comprising the landfill classification system described in items #1 through #4 above are illustrated in **Figure 1** where the gas, temperature, and smoldering fronts are indicated within an anaerobic or normal MSWLF.

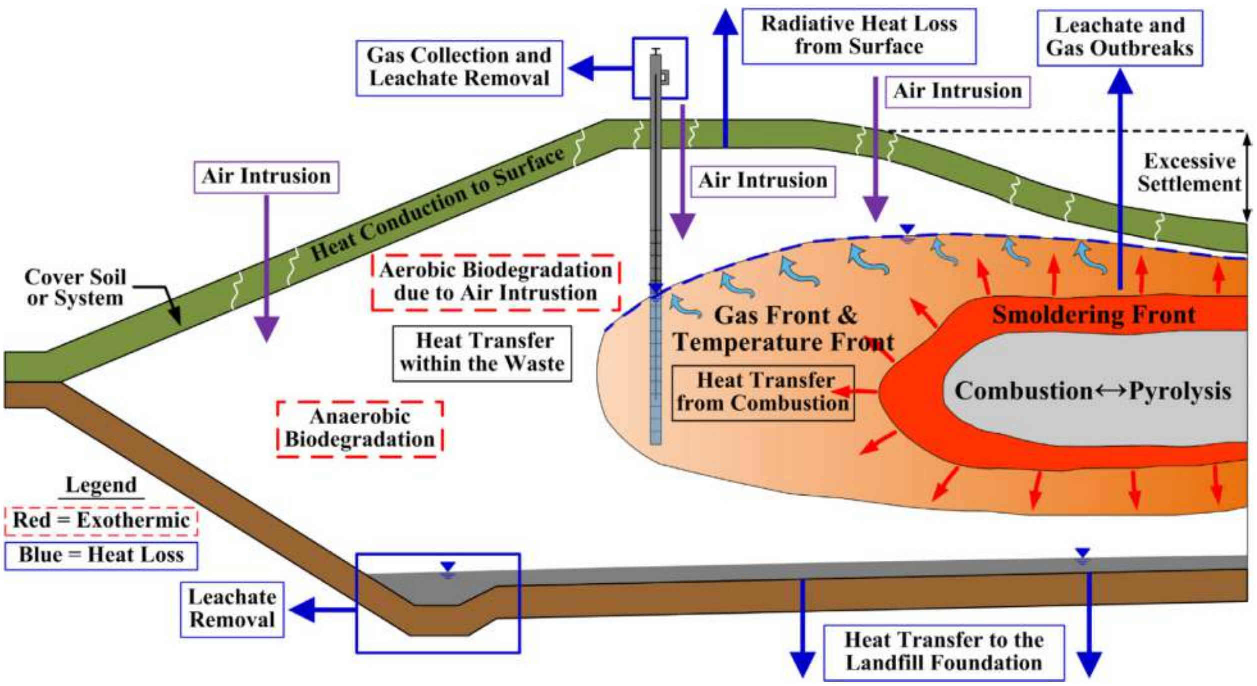

Figure 1: **Schematic of landfill zone with an elevated temperature event illustrating the normal or anaerobic zone, gas front, temperature front, and smoldering front (image from Jafari et al., 2017).**

ETLE TRIGGERS

Factors leading to the triggering of an ETLE include air intrusion, partially extinguished surface fires, waste placed at an elevated temperature, e.g., incinerator ash, exothermic chemical reactions, e.g., spontaneous combustion or aluminum waste(s) reacting with liquid, leachate recirculation in the presence of reactive waste(s), and smoldering combustion. For example, approximately 870 U.S. landfills in 2010 operated an active gas collection system, with 402 or 46% of them reporting at least one elevated temperature event between 2004 and 2010 (Powell et al. 2016). This suggests that landfills with and without gas collection systems are susceptible to develop of elevated temperatures. Several mechanisms can increase gas wellhead temperatures above 149^0F (65^0C), i.e., temperatures above which anaerobic biodegradation is usually curtailed (Farquhar and Rovers 1973; McBean et al. 1995). However, a major contributor to temperatures above 149^0F (65^0C) is introduction of ambient air into a landfill during gas collection and control operations, poor interim soil or posi-shell cover maintenance, such as is occurring in the Bristol MSWLF, and/or air intrusion through the sidewall geosynthetic liner system. The introduction of oxygen creates aerobic conditions that can result in temperatures (60 to 80^0C) that are two to three times higher than those encountered with anaerobic conditions (25 to 45^0C) based on a heat of enthalpy comparison (Jafari et al., 2017). Under aerobic conditions waste temperatures can increase to 176°F (80°C) and higher if smoldering combustion develops.

Although the majority of elevated temperature events are small and/or easily suppressed surface events at the working face, they can develop into large-scale subsurface events with elevated temperatures migrating through the entire facility. Based on observations from large-scale, multi-year landfill case studies, Stark et al. (2012) and Jafari et al. (2016) indicate the expansion of elevated temperatures from a localized area progress as follows: (1) decreased methane (CH_4) to carbon dioxide (CO_2) flow rate ratio with subsequent increase generation and accumulation of carbon monoxide (CO) and hydrogen (H_2) gases; (2) elevated waste and gas wellhead temperatures; (3) increase in gas pressure and flow; (4) increased leachate production, migration, and pressure; (5) possible slope instability; and (6) rapid landfill surface settlement (Jafari et al., 2016). These indicators characterize changes in landfill behavior from normal operating conditions of anaerobic decomposition to elevated temperatures, limited methane production, and waste consumption.

Identifying this landfill progression is important because landfill operators, e.g., City of Bristol, VA, consultants, and environmental agencies need a framework to demarcate the spatial temporal boundary and rate of movement of the ETLE to install instrumentation, an isolation break, i.e., a physical barrier such as a vertical cutoff wall or separation created by excavating waste, to reduce the potential for elevated temperatures consuming a larger portion of the facility. As a result, the classifications presented above, i.e., gas, temperature, and smoldering fronts, were developed to link the progression of indicators listed above to the spatial and temporal characteristics of the elevated temperatures so operational and remedial measures can be devised and implemented to reduce the spread and duration of the ETLE.

PRIOR ETLEs

The data gathered by the authors during prior involvement in ETLEs that have developed in North and South America were used to develop the "front" classification system presented by Jafari et al. (2017) and summarized above. Three of the U.S. ETLEs are discussed in this section because of their relevance to the Bristol, VA MSWLF. The first major ETLE in the U.S. started in early 2005 and involves an 88-acre MSWLF located near Cleveland. This case involves leachate recirculation in an area with previously place aluminum processing waste(s) (Calder and Stark, 2010 and Martin et al., 2013). Aluminum processing waste comes in a variety of forms containing variable amounts of aluminum and reactivity. The terms "dross," "salt cake," "skim," "rich," "white dross," "black dross," "baghouse dust," and other designations refer to the amount of aluminum metal present and the reactivity of the various wastes. Baghouse dust is the most reactive of the wastes because of its high surface area that allows greater contact with liquid and thus greater reactivity. This case is mentioned because moisture resulted in an ETLE otherwise the MSW is not saturated so oxygen can enter, aerobic conditions can develop, and spontaneous combustion can start. Once spontaneous combustion starts, it can initiate a long lasting smoldering combustion event (Jafari et al. 2017). Smoldering is a slow and flameless combustion that generates significant heat, i.e., highly exothermic, that can move via the gas and temperature fronts before the smoldering front arrives and consumes the waste mass. The migration of the gas and temperature fronts occurs more readily in unsaturated than saturated materials. This ETLE did not start in the quarry portion of this facility and the depth of waste in the area/cell in which the ETLE developed was about 200 ft. As a result, this ETLE is not a deep and wet quarry landfill as postulated by Dr. Benson.

Smoldering of MSW can generate temperatures that reach 665°C (1,225°F) as measured in two MSWLFs undergoing smoldering combustion (Stark et al., 2021). Char, scorched earth, smoke, and steam were visible along the landfill surface through cracks and vents, which facilitated air intrusion. Air intrusion was initially facilitated by use of a thin sand cover that is more permeable than a fine-grained soil cover (Stark et al, 2021), which is similar to the insufficient cover conditions present in the Bristol MSWLF. Smoldering combustion cannot occur below a liquid level or in saturated waste because it is thermodynamically impossible. As a result, the only situation where an ETLE can occur in an MSWLF below the leachate level is if a reactive material(s) is present. There is no evidence that the Bristol, VA MSWLF accepted reactive aluminum or other reactive waste(s) so the current ETLE is occurring above the sustained or pooled leachate level in the bottom of the quarry. Installation of the thermocouples recommended below will confirm the depth of the elevated temperatures.

The next two major ETLEs in the U.S. involve quarry landfills. The first quarry MSWLF is near St. Louis, Missouri and involves a 52-acre landfill with a north and south quarry. This ETLE started in 2011 and due to air intrusion around at least one gas well caused by high gas well vacuum pressures pulling oxygen into the waste. The depth of the spontaneous combustion, and subsequently smoldering, is about 60 to 75 ft, which is well above the sustained or pooled leachate level. As the smoldering progressed, waste was consumed above and below the smoldering front resulting in the smoldering moving deeper into the waste and the surface of the MSWLF settling/collapsing over 75 ft as the waste below was consumed. This resulted in the 75 ft of above ground waste disappearing below the quarry walls. This facility was closed and not recirculating leachate when the spontaneous combustion started. To date, a haul road or other feature that separates the southern quarry, where the spontaneous combustion started, from the northern quarry has prevented the smolder from consuming the waste in the north quarry. To date, the entire south quarry has been impacted/consumed by this smolder event resulting in the entire south quarry being near or below the quarry walls.

In the second quarry case near Chicago, the ETLE also started above the sustained or pooled leachate level due to air intrusion around a gas well caused by high gas well vacuum pressures pulling oxygen into the waste. Prior to completion of the gas collection and control system (GCCS) in 2006, three gas wellhead fires occurred, which may have started a larger spontaneous combustion event. Before 2006, minimal maintenance and oversight of the GCCS occurred resulting in high gas well vacuum pressures pulling oxygen into the waste. In addition, reactive wastes could have been placed in this 55-acre MSWLF because of the proximity of heavy industry, e.g., coal combustion residuals, lime, aluminum processing wastes, and other reactive materials. The depth of the measured elevated temperatures in this case is less than 100 ft (27.4 m). The depth to the leachate in the western one-third of the quarry varied with time from 20 to 50 ft.

Given the measured elevated temperatures are at or below the leachate level in the western one-third, a reactive waste may also have contributed to the initiation of spontaneous combustion, and subsequent smoldering. To date, a rock outcrop used as a haul road has contained the ETLE to the western one-third of the quarry because it essentially isolates the western area from the rest of the quarry.

In summary, the trigger of elevated temperatures in MSWLFs is not related to the depth of the waste or the leachate level being in excess of 60 m above the base of the landfill as postulated by Dr. Benson in Appendix C of this expert panel report. At all three of these U.S. MSWLFs that have recently experienced an ETLE, the zone of heat accumulation was not deep but it did expand over time. This resulted in installation of a fire break in the Cleveland facility because the smoldering was propagating through the 88-acre landfill. A haul road, rock outcrop, or other thermal barrier present in the two quarries isolated the smoldering events in the St. Louis and Chicago MSWLFs and to date has prevented the entire facility from being consumed. Unfortunately, aerial photographs from the start of the Bristol, VA MSWLF do not show a haul road or other feature that separates the southern portion of the quarry where the ETLE appears to have started from the northern portion. As a result, care should be taken to quickly control this ETLE so it does not reach a smoldering condition because it could migrate throughout the entire quarry.

BRISTOL, VA MSWLF

To determine the cause of the Bristol, VA MSWLF ETLE, a forensic analysis of the landfill conditions must be conducted. This analysis must examine landfill gas data, landfill gas generation rates, landfill gas to energy contracts, landfill operational and maintenance plans, landfill cover, site conditions, landfill emissions, prior landfill regulatory volitation, landfill management, and other relevant factors. Additionally, the analysis must understand that landfill data is limited in the early stages of an ETLE and using post ETLE data is not recommended without understanding the possible cause(s) of the ETLE.

With this caveat, the cause of the elevated temperatures and landfill emissions from the Bristol MSWLF appears to be due to a change from anaerobic waste decomposition to an aerobic condition within the waste mass. Development of an aerobic condition in the Bristol MSWLF has been facilitated by, in no particular order: (1) operation of the gas well extraction system that has resulted in oxygen being drawn into the waste resulting in oxygen concentrations well above the industry standard of 2% for an interior gas well, (2) insufficient soil and/or posi-shell cover over the exposed MSW allowing oxygen intrusion, and (3) breaches in the quarry sidewall geosynthetic liner system allowing oxygen intrusion and waste emissions to exit.

In particular, **Table 1** shows measured oxygen concentrations and associated gas wellhead temperature increases from the southern portion of the quarry of the Bristol MSWLF. **Table 1** shows most of the data indicate the southern portion of the quarry can be classified as in the temperature front (wellhead temperature > 131^0F) to smoldering front (wellhead temperature > 145^0F) according to Jafari et al. (2017). In general, the elevated temperatures are associated with oxygen concentrations much greater (18 to 21.2%) than the industry standard of 2% for an interior gas well. The interesting gas wells in **Table 1** are #35 and #47 because they show temperatures greater than 120^0F (49^0C) but low oxygen concentrations. This is due to heated gases migrating through the permeable and unsaturated MSW, which corresponds to the gas front shown in **Figure 1**. Of course, the gas front migration could not occur if the waste was submerged so this heat transfer is occurring above the pooled leachate.

Table 1: **Measured Oxygen Concentrations and Gas Wellhead Temperatures in Southern Portion of the Quarry.**

Gas Well Number	Oxygen Concentration (%)	Temperature Increase (^{0}F)
35	0.0 to 3.6% (gas front)	32^0 (92 to 124^0)
39	9.7 to 21.2%	32^0 (68 to 100^0)
40	2 to 18%	64^0 (40 to 102^0)
46	0.5 to 18%	85^0 (70 to 155^0)
47	0.0 to 1.1% (gas front)	46^0 (80 to 126^0)
66	1.2 to 7.3%	65^0 (93 to 158^0)
67	1.2 to 6.7%	28^0 (130 to 158^0)
68	2.6 to 3.9%	27^0 (93 to 120^0)

Table 2 shows measured oxygen concentrations and associated gas wellhead temperatures from the northern portion of the quarry of the Bristol MSWLF. In particular, **Table 2** shows most of the data indicate the northern portion of the quarry is also in the temperature front (wellhead temperature > 131^{0}F) to smoldering front (wellhead temperature > 145^{0}F) according to Jafari et al. (2017). In general, the elevated temperatures are associated with oxygen concentrations much greater (12 to 20.5%) than the industry standard of 2% for an interior gas well. The interesting gas wells in **Table 2** are #31R, #32R, and #37 because they show temperatures greater than 120^{0}F (49^{0}C) but low oxygen concentrations. This is due to heated gases migrating through the permeable and unsaturated MSW, which corresponds to the gas front shown in **Figure 1**.

Gas well #32 in **Table 2** is even more interesting because it shows oxygen concentrations less than 3% and temperatures less than 100^{0}F (38^{0}C). This means the gas front probably has not reached gas well #32 and the landfill is still in the normal or anaerobic condition at this well. It appears that gas well #32 is near well #32R at the northern end of the quarry, so the gas front has not permeated as far north as gas well #32. This suggests the ETLE may be migrating from the south to the northern portion of the quarry.

Table 2: **Measured Oxygen Concentrations and Gas Wellhead Temperatures in Northern Portion of the Quarry.**

Gas Well Number	Oxygen Concentration (%)	Temperature Increase (^{0}F)
29	1.0 to 20.5%	46^0 (60 to 102^0)
29R	0.5 to 20.5%	40^0 (80 to 120^0)
31R	0.1 to 2.7% (gas front)	44^0 (102 to 156^0)
32	0.1 to 2.6% (gas front)	44^0 (64 to 86^0)
32R	0.4 to 2.7% (gas front)	20^0 (105 to 125^0)
33	0.5 to 12.0%	80^0 (50 to 130^0)
37	0.0 to 0.9% (gas front)	52^0 (80 to 132^0)
62	0.0 to 10.0%	60^0 (70 to 130^0)
64	1.2 to 9.2%	23^0 (135 to 158^0)
65	1.2 to 7.3%	65^0 (93 to 158^0)

This data indicates that most of the Bristol, VA MSWLF is experiencing aerobic conditions, which can lead to additional spontaneous combustion. The development of the aerobic condition has been facilitated by, in no particular order: (1) high gas well vacuum pressures pulling oxygen into the waste, (2) insufficient soil and/or posi-shell cover, and (3) breaches in the quarry sidewall liner system not surface water infiltration and/or submerged waste. In fact, surface water infiltration would help suppress or slow the migration of the smoldering combustion because there is no evidence to date that reactive wastes have been deposited in the Bristol, VA MSWLF. As a result, the remedial measures presented below are designed to reduce oxygen intrusion into the waste and eliminate spontaneous combustion, which can result in smoldering combustion.

REMEDIAL MEASURES

The main objective of the expert panel is to reduce the landfill emissions/odors. Afterwards, the feasibility of continued operation of the MSWLF should be considered. Given the main objective and the ETLE appears to be caused by oxygen (air) intrusion, the remedial measures should initially seal the top and sides of the MSWLF. To achieve the main objective and allow future operation of the MSWLF the following actions are recommended:

- Install a geosynthetic cover system over the entire Landfill to seal the surface of the LF.
- Seal the sidewall geosynthetic liner system to the rock walls. To accomplish this seal, the damaged geosynthetic liner system should be pulled back or cut, shotcrete applied the exposed rock wall to seal joints and cracks, a system of lateral gas collection pipes installed around the perimeter, and a fine-grained soil barrier compacted against the rock wall to seal the perimeter to the shotcrete covered rock wall.
- Improve performance of existing gas extraction wells including reducing oxygen intrusion to less than 2%.
- Installation of a dedicated system to monitor landfill temperatures for greater spatial resolution (horizontal and vertical) of the elevated temperatures using thermocouples and to provide data at a greater frequency.
- Installation of five deep wells to enable sampling and characterization of leachate.
- Installation and operation of large-diameter dual-phase extraction wells for removal of gas and heat from the landfill without introducing oxygen into the waste. Extract and treat leachate also extracted from these wells.
- Develop and implement an effective and sustainable stormwater management plan for the landfill that allows water to collet in the southeast corner of the quarry before removal from the quarry.
- Following mitigation of the emissions, elevated temperatures, and high oxygen levels, resumption of landfill operations may be feasible.

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