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# Spatial and temporal characteristics of elevated temperatures in municipal solid waste landfills

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The authors appreciate the writer's comments and industry's perspective related to our paper on elevated landfill temperature events (ETLEs).

The authors agree that the factors leading to elevated temperatures have evolved since Calder and Stark (2010) first reported on the reactivity and disposal of aluminum production wastes (black dross, salt cake, and baghouse dust) in a Subtitle D landfill. Air intrusion from aggressive over vacuum being applied to gas wells also is an important mechanism leading to ELTEs, as indicated by Powell et al. (2016). Jafari et al. (2017a) also list partially extinguished surface fires, disposal of reactive wastes (incinerator ash, aluminum dross, lime stabilized wastes, etc.), high temperature loads, and spontaneous combustion, which were also stated by the Comment authors. Jafari et al. (2017b) provide further discussion on the causes of ETLEs. While the specific mechanism resulting in elevated temperatures is site and operation specific, the progression of ELTEs in Subtitle D facilities has been found consistent across several major case histories (CEC, 2011; Ettala et al., 1996; Frid et al., 2010; Hogland and Marques, 2003; Illinois EPA, 2010; Øygard et al., 2005; Stark et al., 2012) that were not discussed in the paper due to space restraints. The data and trends from all of these case histories were used to form the general landfill spatial classification system proposed by Jafari et al. (2017a), which is possible because of the similarity in the disposed wastes.

Smoldering is a limited, intermittent reaction (Ohlemiller, 2002; Rein, 2009) that can occur under oxygen conditions of less than 3% v/v (DeHaan, 2006; Malow and Krause, 2008; Radojevic, 2003) and can persist within a solid waste landfill between 212°F and 250°F (Ettala et al., 1996). If sufficient oxygen is not present to initiate and sustain smoldering, it will cease. This is exemplified in the trends observed in Figs. 9 and 10 of Jafari et al. (2017a). In Fig. 10(c), the measured nitrogen ($N_2$) and oxygen ($O_2$) levels in GW-B at an elapsed time of five (5) months are 30% v/v and 2.3% v/v, respectively. Using the $N_2$ to $O_2$ ratio of 3.76 for ambient air, the concentration of $O_2$ is approximately 8% v/v. The difference between 8% v/v to 2.3% v/v in the gas well suggests oxygen was consumed in an exothermic aerobic reaction. This corroborates the sudden and significant increase in the cumulative movement after month 6 in Fig. 10(d) and the change in temperature contours observed in the downhole temperature arrays (DTAs) from Fig. 9(c) to (d). In addition, Figs. 9(d)-(e) and 10(c)-(d) show that when the $N_2$ level decreased to less than 5% v/v, the ETLE remained stationary within the landfill area between DTA-1 and DTA-4. As a result, smoldering can start and stop depending on the availability of $O_2$ and is not a continuous process in ETLEs although it can be if the soil cover is not maintained.

Site 2 is a former quarry site that was transitioned into a municipal solid waste (MSW) facility. MSW exists approximately 73 m below the quarry wall and 25 m above ground surface. The ETLE started in the southeast section of the facility in the waste mass above the quarry walls. This was evident from leachate outbreaks on the side slopes and localized settlement depressions near gas extraction wells. Following development of the ELTE, a settlement bowl formed encompassing the southern portion of the landfill. Prior to the ETLE, the leachate levels were understood to be at a depth of 10 m above the quarry base. Because of an inward gradient and difficulty in extracting liquids during ETLEs, the leachate level eventually rose to the height of the quarry wall. Most of MSW above the quarry wall had been consumed by this time. For Site 1, while the initial moisture content (20–40%) can increase, it is difficult to parse out municipal solid waste (MSW) into its components to suggest the waste is saturated because moisture is held in the pores spaces and inherently in the materials. Finding charred waste can be difficult in the landfill because of the heterogeneity of the waste mass. This is exacerbated by the difficulty in boring through the epicenter of the ETLE, where significant elevated gas and leachate pressures exist. Nevertheless, evidence of charring has been found in an MSW experiencing an ETLE, as shown in Fig. 1.

The authors are in agreement with many of the aspects of ETLEs in the Comment, including that many initiation mechanisms exist. In particular, an initial source of heat elevates the temperature in a portion of the landfill thereby promoting self-sustaining exothermic reactions that propagate spatially from the original location/source (Barlaz et al., 2017). A series of landfill indicators demonstrate the progression of the ETLE in the landfill, as is

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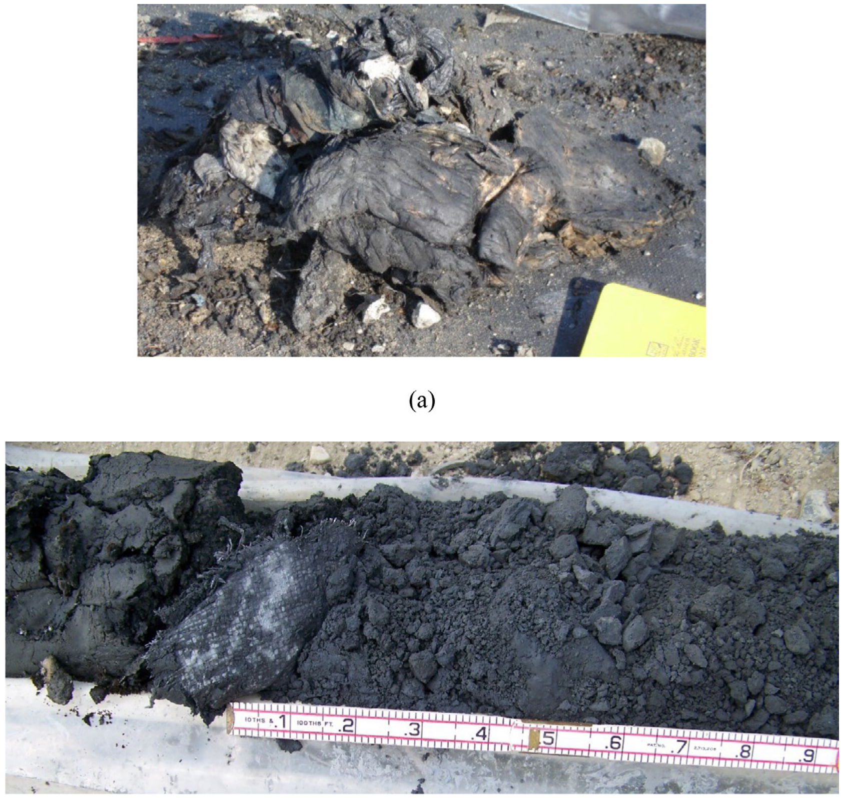

(a)

(b)

**Fig. 1.** Photographs of charred MSW during an ETLE from: (a) a bucket auger boring and (b) a rotosonic boring.

described by Jafari et al. (2017b). This progression will continue unless a physical separation isolates the ETLE from the remainder of the landfill.

A point of ongoing discussion will be if pyrolysis is exothermic and under what conditions in landfills this may be relevant. It is well understood that the landfill industry cannot acknowledge the role of smoldering or combustion in an ETLE because of the regulatory and legal ramifications. However, this line of reasoning fails to acknowledge the most important outcome of an ETLE; that is, at elevated temperatures (e.g., above 80 °C) the integrity of environmental control systems (gas extraction wells, leachate collection pipes, flare system, surface cover system, e.g., soil or geosynthetic, and most importantly the bottom liner system) can become compromised (Jafari et al., 2014).

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# Spatial and temporal characteristics of elevated temperatures in municipal solid waste landfills, Navid H. Jafari, Timothy D. Stark, and Todd Thalhamer, *Waste Management*, 2017, Vol. 59, p. 286–301

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**Article Comment**

The subject article presents data from two landfills that are experiencing elevated temperatures and uses these data to present a "landfill classification system" to generalize the manner in which elevated temperatures spread. The authors have presented valuable data that contribute appreciably to the body of knowledge regarding elevated temperature landfills. However, we have concerns regarding inferences in the article, and the presentation of a general classification system, given that knowledge of the underlying mechanisms responsible for elevated temperatures is evolving. We also believe that readers should be aware of other considerations in diagnosing landfills that are experiencing elevated temperatures. In this Comment, we highlight areas where we believe that additional diagnosis of the data sets is warranted.

Jafari et al. infer that elevated temperatures in landfills are a consequence of subsurface oxidation events specifically related to air intrusion. However, there is insufficient evidence to support the availability of continuous oxygen as would be required to support a combustion or smoldering front as described in the article. Considering Site 2, the data in Figure 10 of Jafari et al. indicate that there is insufficient oxygen to support combustion. Oxygen from air intrusion into a landfill would bring an associated amount of nitrogen at a fixed ratio (nitrogen to oxygen) of 3.76. During combustion, smoldering or otherwise, oxygen would be consumed, producing $CO_2$ or CO or both, as well as water. This would lead to an increase in the ratio of nitrogen to oxygen and enrichment of the landfill gas in nitrogen because the water that is produced during combustion is normally not measured. The nitrogen concentrations in Fig. 10 (only 4 measurements above ~10%) are inconsistent with the air intrusion that would be needed to support combustion, including smoldering.

A second consideration in evaluating oxygen availability is the potential for oxygen transport. Most of the waste at Site 2 was submerged (Benson, 2017), which would inhibit oxygen transport even if oxygen was present. Similarly, much of the waste at Site 1 was also extremely wet or saturated, again making oxygen transport difficult and subsurface aerobic oxidation processes unlikely.

A third indicator of combustion or smoldering is temperature. Temperatures at or near a combustion zone and smoldering front would be 700–800 °C or higher (Rein, 2009; Ohlemiller, 1986). We agree with Jafari et al. that temperature data are difficult to obtain, but are unaware of any data from elevated temperature landfills that would corroborate temperatures consistent with those associated with combustion or smoldering. Residuals associated with such high temperatures (e.g., molten plastic) are also not commonly encountered during intrusive activities (e.g., bucket auger borings for gas wells) at elevated temperature landfills.

Given the absence of continuous oxygen, the abundance of water, and the absence of temperature data consistent with smoldering or combustion, the rationale for assuming aerobic subsurface oxidation as the cause of elevated temperatures is unclear, as is the rationale for not exploring other mechanisms more consistent with the data. The need to explore alternatives to aerobic processes is critical, and has a profound effect on the interpretation and classification of data from elevated temperature landfills. Specifically, the published data emphasize the need to consider an exothermic anaerobic process.

Our research suggests that exothermic pyrolysis is a more likely mechanism responsible for elevated temperature landfills. We understand that the literature regarding the energetics of pyrolysis can be confusing, with many reports describing pyrolysis as an endothermic process (including the subject article by Jafari et al.). However, exothermic pyrolysis of biomass has been demonstrated to be a mechanism for a self-propagating reaction that releases heat in the absence of oxygen (Mok and Antal, 1983, Park et al., 2010, Ciuta et al., 2014).

Pyrolysis of lignocellulosic materials (e.g., cellulose, hemicellulose, and lignin), which are major components of municipal solid waste and can be considered as biomass, has been extensively

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investigated (Orfão et al., 1999). For example, Mok and Antal (1983) and Antal and Gronli (2003) demonstrate that pyrolysis of cellulose includes endothermic and exothermic stages. In the endothermic stage, a combination of external heat and the persistence of volatiles is required to raise the temperature to initiate an exothermic stage where the reaction itself provides sufficient heat to be self-sustaining. Exothermic pyrolysis yields char, tar, condensable volatile species, $H_2$, CO, $CO_2$, and $H_2O$ – products that are present in elevated temperature landfills. The presence of CO, which Jafari et al. use to infer subsurface oxidation, is also consistent with pyrolysis.

There is good reason to consider exothermic pyrolysis as the underlying mechanism in elevated temperature landfills. In studies on charcoal production from biomass, Antal and Gronli (2003) report that the energetics of pyrolysis can transition from endothermic to exothermic as the fluid pressure increases. In addition, exothermic conditions were favored when gases generated during decomposition of the feedstock were allowed to accumulate. These gases contain volatile organics that are pyrolytic substrates. Although the studies were not conducted on MSW, which contains additional organics that could be expected to react (e.g., plastics, textiles) along with aluminosilicate catalysts (Zhang et al., 2016), they serve as a potential analog to landfills. For example, localized stagnant gases and elevated gas pressures in landfills can result from a gas collection well(s) that is flooded and therefore not effectively removing gas.

There is much to be learned about exothermic pyrolysis as it applies to landfills, including processes that initiate pyrolysis and the rate at which pyrolysis propagates. Nonetheless, self-propagating exothermic pyrolysis must be considered. Our evolving but incomplete conceptual model of elevated temperature landfills relies on an initiating source of heat that elevates temperatures in a portion of the landfill to temperatures substantially above normal, and promotes self-sustaining exothermic reactions that propagate spatially from the original source. There are a number of potential mechanisms that could result in the accumulation of sufficient heat to initiate pyrolysis, including disposal of a hot load, interactions of landfill liquids and gases with reactive waste, a surface fire that was extinguished but not fully cooled prior to being covered with additional waste, local aerobic reactions (e.g., from over pulling on a gas well), and/or insufficient heat removal (Hao et al., 2017).

In conclusion, we applaud the authors for publication of data from elevated temperature landfills, as these data will help to educate the solid waste landfill community and lead to important discussions amongst interested parties. However, we recommend that the solid-waste community exercise caution regarding generalizations and conclusions regarding elevated temperature landfills until the underlying mechanisms are thoroughly understood. Until a sound understanding of the underlying mechanisms responsible for initiation and propagation of heat is developed and confirmed by the science and engineering community, we believe that embracing a generalized model or classification scheme is inappropriate, potentially dangerous, and could lead to incorrect actions for management or remediation. In fact, our collective experience at a number of elevated temperature landfills suggests that causes, conditions, and management strategies are highly site-specific.

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