Progression of Elevated Temperatures in MSW Landfills

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Abstract: Elevated temperatures in municipal solid waste landfills can pose health, environmental, and safety risks because they can generate excessive gases, liquids, pressures, and heat that can damage landfill infrastructure. This paper discusses mechanisms that can lead to elevated temperatures in the landfill and presents a case history to establish trends in gas composition, leachate collection, settlement, and slope movement. In general, landfill gas composition changes from predominantly methane (50-60% v/v) and carbon dioxide (40-55% v/v) to a composition of carbon dioxide (60-80% v/v), hydrogen (10-35% v/v), and carbon monoxide (> 1,500 ppmv) as temperature elevate. As waste temperatures increase, gas and leachate pressures also increase, resulting in odors, leachate outbreaks, and potential slope instability. These observations are summarized in a progression of elevated temperature indicators that are related to field manifestations and possible remedial measures.

INTRODUCTION

Elevated temperatures have been documented in municipal solid waste (MSW) landfills, construction demolition debris landfills, industrial waste fills, and sanitary dumps (Martin et al. 2013; Sperling and Henderson 2001; Ettala et al. 1996; Øygard et al. 2005; Koelsch et al. 2005; Frid et al. 2009). The presence of elevated temperatures, particularly in MSW landfills, can impact the integrity of the cover and liner systems, leachate quality, gas composition, slope stability and differential settlement, odor mitigation, and abatement operations (Øygard et al. 2005; Jafari et al. 2014; Stark et al. 2012). In addition, they present a significant threat to the environment by emitting to the atmosphere incomplete combustion by-products, reduced sulfur compounds, and particulate matter (Ruokojarvi et al. 1995).

MSW landfills with a gas collection and control system used to comply with federal regulations (40 Code of Federal Regulations (CFR), Part 60, Subpart WWW) are required to operate each gas extraction well with a landfill gas temperature less than

55°C (131°F) because methane production from mesophilic bacteria during anaerobic biodegradation can start to significantly decrease above this temperature (Kasali and Senior 1989; Hartz et al. 1982). Therefore, this paper considers elevated temperatures in MSW landfills to be demonstrated by gas wellhead temperatures above 65°C because anaerobic biodegradation is curtailed.

Techniques are readily available to detect elevated temperatures (Stearns and Petoyan 1984; Stark et al. 2012; Martin et al. 2013; Sperling and Henderson 2001), but a comprehensive understanding of the spatial and temporal variation of landfill gas, temperature, leachate migration, and settlement of elevated temperature events and the underling mechanisms are lacking. As a result, this paper presents a case history to relate elevated gas and waste temperatures, changes in gas composition and production, leachate migration, slope movement, and settlement into a progression of landfill indicators. The progression of indicators are linked to field manifestations and possible remedial measures are suggested. In addition, this paper also discusses the development of elevated temperatures leading to the progression of indicators.

CASE STUDY

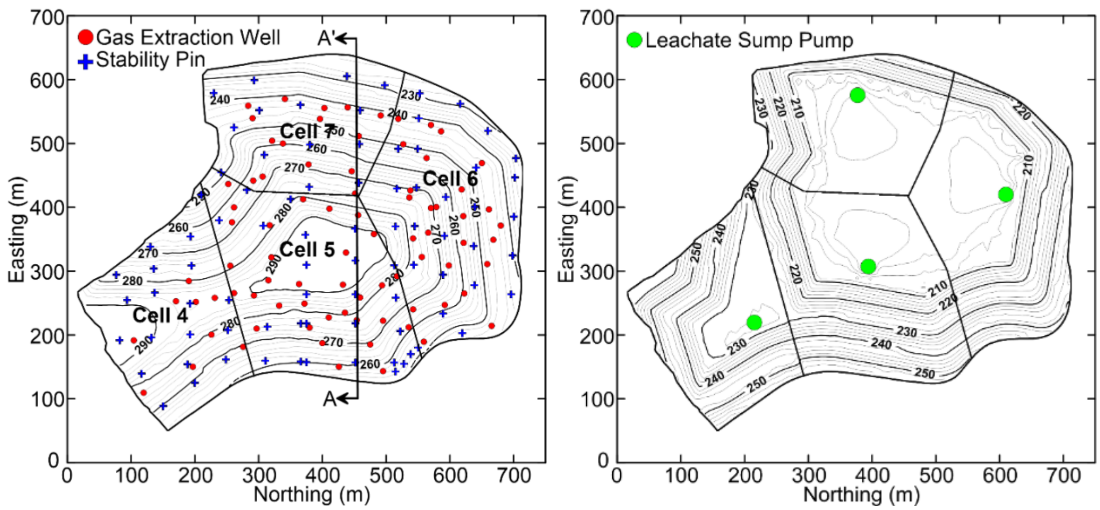
The case study presented herein is a MSW landfill regulated under Subtitle D regulations. The site is permitted for waste disposal in 178 ha and receives up to 9,000 metric tons of MSW per day. Fig. 1 shows the impacted area in Cells 4 – 7. These cells encompass 26.2 ha and were constructed in phases, with Cell 4 completed in late 1997, Cell 5 in early 1999, Cell 6 in late 1999, and Cell 7 in early 2001. After reaching the permitted elevations in 2005, Cells 4 through 7 were capped with intermediate 0.6 m of fine-grained soil and a gas control and collection system was installed.

In August 2009, five gas wellheads in Cell 5 experienced temperatures above 68°C and as high as 95°C. Associated laboratory gas sampling from the wellheads reported CO >1,000 ppmv, with a maximum of 10,200 ppmv (Ohio EPA 2010). Based on the Findings and Orders (Ohio EPA 2010), the facility initiated an expanded monitoring program to monitor and delineate the elevated temperatures. The program included:

- Weekly measurements of gas wellhead temperature, flow rate, and pressure.
- Weekly measurements of CH_4, CO_2, N_2, O_2, H_2, and CO with a portable field gas chromatograph.
- Monthly topographic survey.
- Monthly measurement of stability pins (slope movement and elevation).
- Weekly downhole temperature measurements in Cell 4.

Gas temperature, flow rate, and vacuum pressure were sampled at the gas port located on the wellhead (located above the surface) and recorded using the GEM™ 2000 meter (LandTec 2010). Fixed gases (CO_2, CH_4, N_2, O_2, H_2, and CO) were measured by a portable field gas chromatograph. Stability pins installed into the cover system are used to monitor changes in northing, easting, and elevation. Downhole temperatures were obtained from Type T thermocouples installed in sand backfilled boreholes. Leachate was collected and removed at sumps located in each cell (Fig. 1(b)). The facility reported the number of hours each sump was operated. Although the volume of leachate is unknown, a comparison between sump operations can be used to infer the migration of leachate into each cell.

Elevated temperatures were first observed in Cell 5, and they migrated to Cells 6 and 7 over the next four years. During the monitoring period, Cell 4 remained unaffected by elevated temperatures. Data collected from the monitoring program is discussed herein to show the correlations and sequence of temperature increase to changes in gas composition and pressure, slope movement, and settlement. Fig. 1(a) shows the location of gas extraction wells and stability pins used to correlate landfill trends. Fig. 1(b) shows the liner system contour elevations.



(a) (b)

FIG 1. Plan view of Cells 4 through 7 showing: (a) location of gas extraction wells and stability pins, (b) leachate and composite liner system elevations

Change in Landfill Gas Composition

Temperatures in MSW landfills operate within the mesophilic range of 38 – 54°C (EMCON 1981; Yesiller et al. 2005). The mesophilic bacteria that regulate methane generation occur best within a temperature range of 40 to 42°C (Hartz et al. 1982; Pfeffer 1974). Although there is not a simple upper temperature limit for methanogens, laboratory reactors simulating anaerobic decomposition of MSW indicate that the methane production starts to significantly decrease if waste temperature exceeds 55°C (Kasali and Senior 1989; Hartz et al. 1982). This decrease is attributed to mesophilic bacteria population being significantly curtailed (Farquhar and Rovers 1973). The temporal relationship with methane production and temperature increase has yet to be investigated. As a result, Fig. 2 shows the relationship between increasing wellhead temperature and changes in the ratio of CH_4 to CO_2 flow rate, H_2 levels, and CO concentrations for a single gas extraction well.

During anaerobic biodegradation, landfill gas is composed mostly of methane (45–60% v/v) and carbon dioxide (40–60% v/v), so a ratio of CH_4 and CO_2 close to unity provides a useful measure of degree of microbial activity (Barlaz et al. 2010; Powell et al. 2006). In addition, the advantage of using CH_4 and CO_2 flow rates rather than concentrations is that flow rate is a measure of the actual gas production from the waste mass. Wellhead temperatures were used to standardize the flow rates to standard pressure and temperature of 20°C and 101 kPa. Temperature and flow rate were measured at the gas wellhead using the gas analyzer GEM™ 2000, while gas concentrations were measured by a portable field gas chromatograph.

In Fig. 2(a), the gas extraction well is operating under normal conditions because wellhead temperatures are below NSPS limit of 55°C and the ratio of CH_4 to CO_2 is greater than unity (see Fig. 2(b)). Conditions remain steady until an elapsed time of 550 days when the ratio of CH_4 to CO_2 precipitously decreases from 1.2 to 0.3 in 50 days (time = 600 days). Wellhead temperatures exceeded the NSPS threshold of 55°C at time of 580 days, i.e., about a month after methane levels began decreasing, and gradually increased to 75°C at t= 800 days. Decreasing ratio of CH_4 to CO_2 before wellhead temperatures increase is a trend among several gas extraction wells at this facility. The delay before wellhead temperature increase may be attributed to the difference in gas flow and heat conduction through the landfill. For example, heat conduction is a slower process than gas flow to an extraction well, so elevated temperatures may arrive after gas has been removed. This observation suggests that changes in gas composition can project in front of the elevated temperatures, with increasing wellhead temperatures an indication of the approaching elevated temperature event.

Hydrogen levels were < 2% v/v and CO was not measured when the ratios of CH_4 to CO_2 remained above unity. Fig. 2(c) shows that H_2 increased at t= 550 days to a maximum concentration of 20% v/v. Similar to H_2, CO increased to ~1,800 ppmv at an elapsed time of t= 550 days, and remained in the range of 2,000 to 2,500 ppmv for the duration of the monitoring period. Combining the timeline in Fig. 2(b) to 2(d), it is evident that changes in the ratio of CH_4 to CO_2, H_2, and CO occur at the same time. Moreover, the ratio of CH_4 to CO_2 and carbon monoxide are characterized by steep slopes, i.e., changes occur in short time frame, while H_2 increase occurs at a slower pace, similar to the wellhead temperature trend.

Elevated Gas and Leachate Pressures

Table 1 shows that MSW landfills under anaerobic biodegradation typically exhibit pressures up to 3 kPa. Stark et al. (2012) found that gas pressures increased to 45 kPa in areas where APW reactions were occurring. In addition, subsurface combustion are found to display significant gas pressures, in some cases as high as 75 kPa. Several mechanisms can contribute to increased gas pressures. Following the ideal gas law and assuming a landfill is a constant volume boundary, gas temperature and pressure increase simultaneously. For example, landfill gas is approximately atmospheric pressure (101.3 kPa) at a temperature of 40°C (Young 1992; Bogner et al. 1988). If subsurface temperatures increase to 100°C, internal gas pressures should increase by 19.5 kPa and thereby reducing the effective stress acting on the waste. Convection can also drive hotter gases to the surface where they can accumulate under a geomembrane liner or emanate from the soil cover system and result in odors. Furthermore, warmer gases carry higher percentage of water vapor that can condense and clog the gas collection system wells and lateral headers. The clogged wells can reduce gas extraction capability, thus permitting subsurface pressures to build-up. Similar to the APW reaction reported in Stark et al. (2012), elevated temperatures can initiate gas generating processes, such as combustion and pyrolysis. For example, Baggio et al. (2008) report that pyrolysis at 500°C of 1 kg of MSW generates around 300 g of gas, which suggests elevated gas pressures could be explained by the increased gas production caused by combustion and pyrolysis. In conjunction with additional gas production, temperatures can damage and/or compromise gas extraction wells and lateral headers. Eventually, the gas collection system can become overwhelmed and lead to elevated gas pressures.

Table 1. Summary of gas pressures for various landfill processes

Landfill Process	Gas pressure (kPa)	Reference
Biodegradation	0.5 – 3	Bogner et al. 1988
Aluminum reaction	0.5 – 45+	Stark et al. 2012
Subsurface combustion	5 – 75+	Author's files

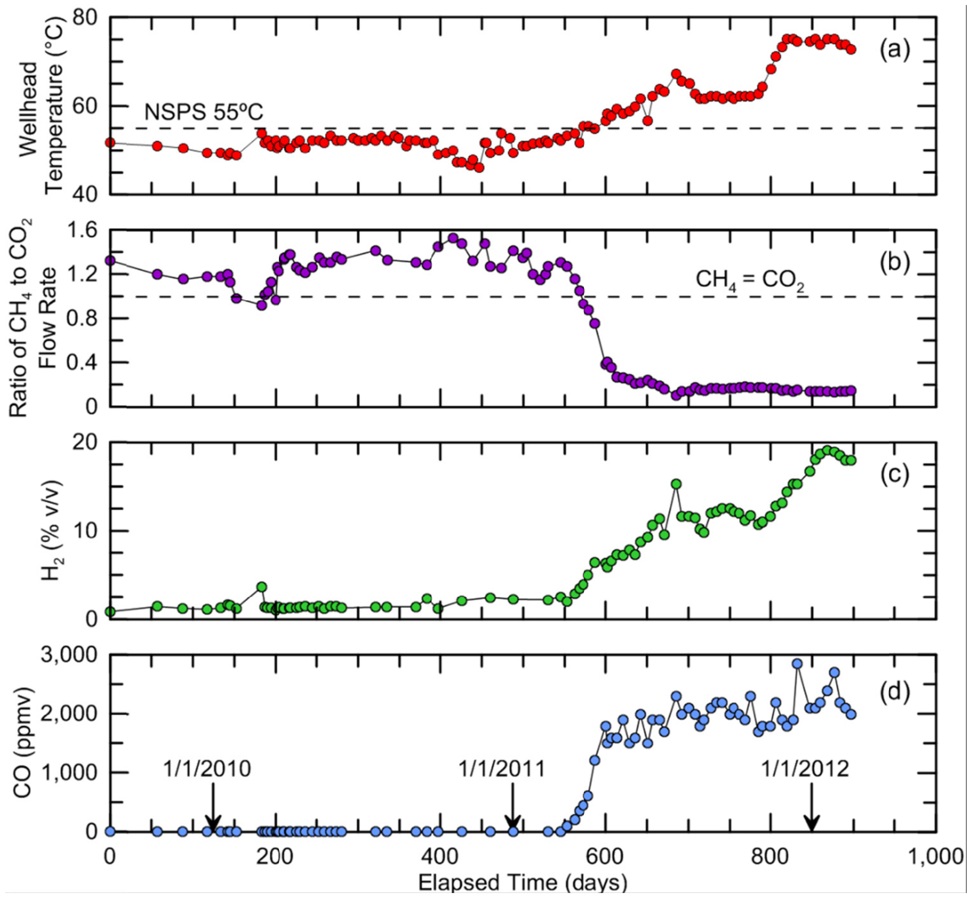


FIG 2. Gas extraction well trends in (a) temperature, (b) ratio of CH4 to CO2 flow rate, (c) hydrogen, and (d) carbon monoxide

Leachate and Moisture Migration

The convection of moisture rich gas from dehydration of MSW can facilitate redistribution of leachate within the waste mass. When water vapor condenses, it can gravitate to the leachate collection system and contribute to increased leachate volume.

Fig. 3 shows the cumulative number of operated hours for each sump in Cells 4 through 7. The sump locations are shown in Fig. 1(b). The data was collected bi-monthly and represents the number of hours the pump was operated. Fig. 3 does not quantify if leachate volume increased, but it allows a comparison of sump productivity as the elevated temperature area expands. Based on Fig. 3, Cell 5 and Cell 7 sump operation significantly increased during the monitoring period. For example, Cell 5 sump operated for ~7,000 cumulative hours while Cell 7 sump reached almost 16,000 hours of operation by November 2013. In contrast, Cells 4 and 6 were operated for only ~2,000 hours after 1,500 days. Elevated temperatures were first observed in Cell 5 and gas wellheads reported temperatures of 95°C. Because subsurface temperatures are higher than wellhead temperatures (Martin et al. 2013), sufficient heat is present to drive moisture from the MSW, where it condenses in gas extraction pipes and/or gravitates to one of the sumps. For example, water vapor and leachate moisture are gravitating to Cell 5 and Cell 7 sumps as temperatures advance into Cell 7. Although Cell 6 is affected by the elevated temperatures, Fig. 3 shows that the sump operation is lower. A possible explanation is that the zone of elevated temperatures is migrating from Cell 5 to Cell 7 so moisture is projected towards Cell 7 instead of Cell 6. In addition, the leachate sump in Cell 4 is located 20 m above Cell 5 sump so leachate drainage and pump operation hours are significantly lower.

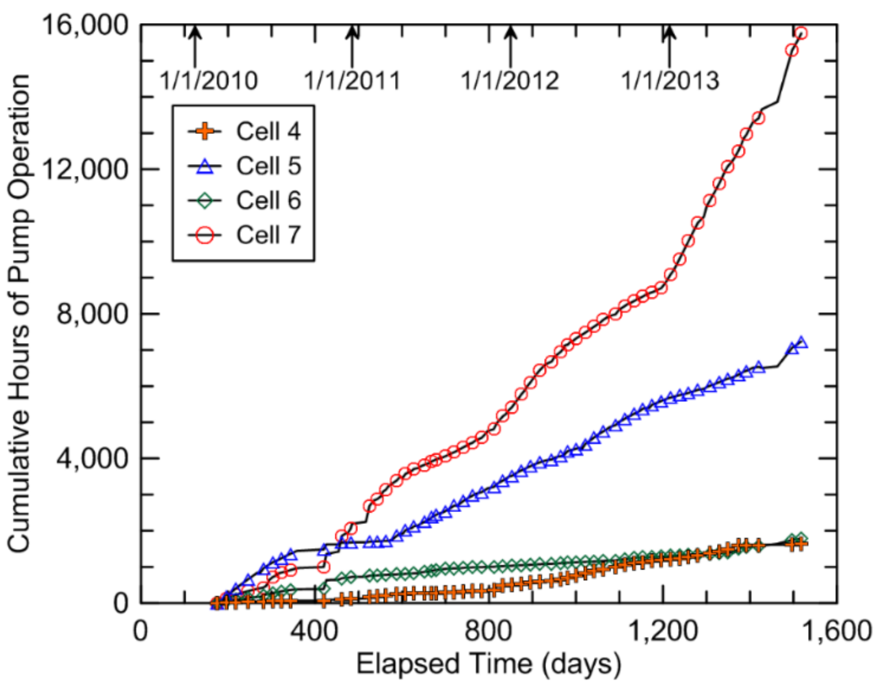


FIG 3. Leachate pumped from sumps located in Cells 4 through 7

Slope Movement and Settlement

Slope instability and movement have occurred at landfills with elevated temperature, leachate, and/or gas pressures (Stark et al. 2012; Koelsch et al. 2005; Jafari et al. 2013; Hendron et al. 1999). The failure described by Stark et al. (2012) resulted in over 6 m of displacement and waste being located outside of the permitted landfill boundary. In general, slope movement is preceded and accompanied by forceful gas and leachate outbreaks. Mechanisms for slope instability include elevated gas pressures, perched leachate surfaces, and/or reduced MSW shear strength (Stark et al. 2010). For example, the interconnecting plastics and other reinforcing materials that contribute to the high shear strength of MSW are most likely consumed, degraded, burnt, and/or decomposed at elevated temperatures.

In addition, excessive and rapid is typically associated with elevated temperatures because the waste is thermally degraded into ash. Stark et al. (2012) report the maximum settlement of the top of a Subtitle D landfill was ~21 m (70 ft), where the initial waste thickness was about 45.8 m (150 ft). The case study reported in this paper also experience rapid settlement. From September 2010 (settlement first recorded) to September 2013, Cell 5 settled over about 20 m (65 ft). The initial waste thickness was 92 m (300 ft), resulting in vertical strain of ~22%.

PROGRESSION OF INDICATORS

The case study identifies the following landfill indicators after the onset of elevated temperatures. Next, spatial and temporal relationships were investigated in order to arrange the landfill indicators into a chronological sequence. For example, cross-section A-A' in Fig. 1(a) extends from Cell 5 to Cell 7, bisects the elevated temperature region, and is used to highlight when gas composition changes along a line of gas wells. The profile of cross-section A-A' and location of gas extraction wells B-1 to B-6 are shown in Fig. 4. Furthermore, a stability pin and gas extraction well in Cell 5 provide a temporal comparison of gas composition and settlement.

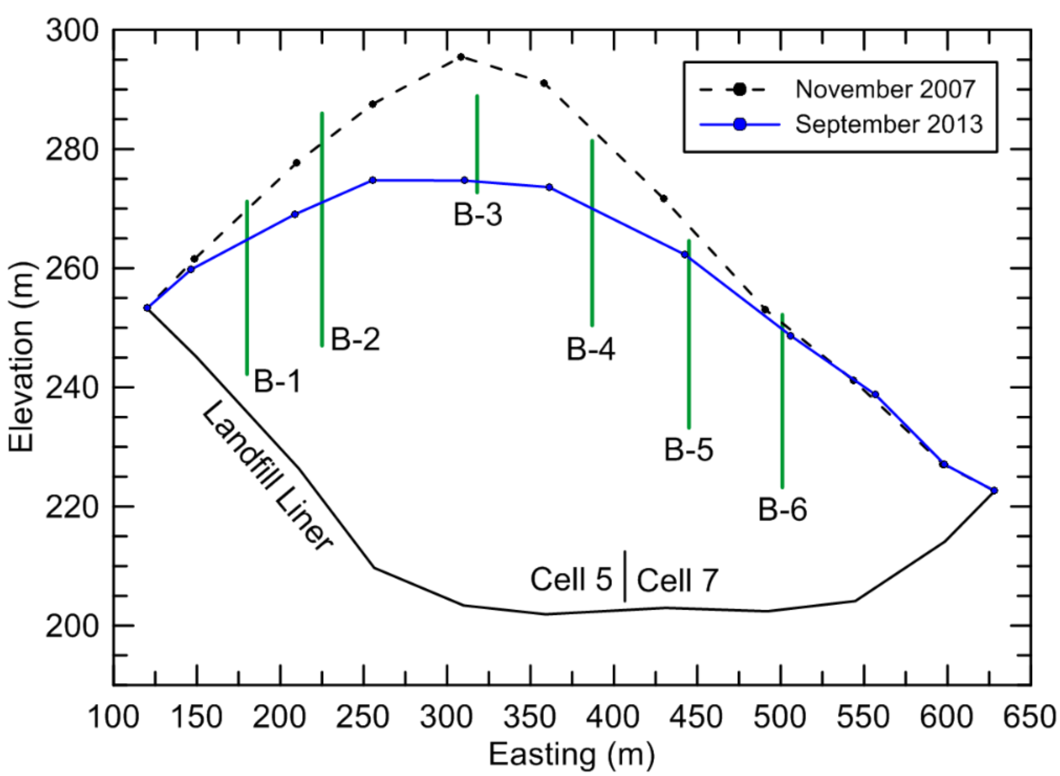


FIG 5. Profile of cross-section A-A' showing gas extraction wells B-1 to B-6 and landfill surface in November 2007 and September 2013

Fig. 5 shows the trends in the ratio of CH_4 to CO_2 for gas extraction wells B-1 through B-6 in cross-section A-A'. Gas wells B-1 and B-2 are located within the initial elevated temperature zone in Cell 5, so the CH_4 to CO_2 ratio is about 0.1 in September 2009 and remains below 0.2 throughout the monitoring period. However, gas wells B-3 through B-6 are located outside of the immediate hot spot and they show CH_4 to CO_2 ratio values near unity from September 2009 to December 2010. In February 2011, the ratio of CH_4 to CO_2 rapidly decreases in each well to values below 0.3. The decline in each well suggests that internal landfill processes change simultaneously even though the distance from B-3 to B-6 is about 250 m. In other words, gas generated from the elevated temperature region is projecting in advance of the elevated temperature front.

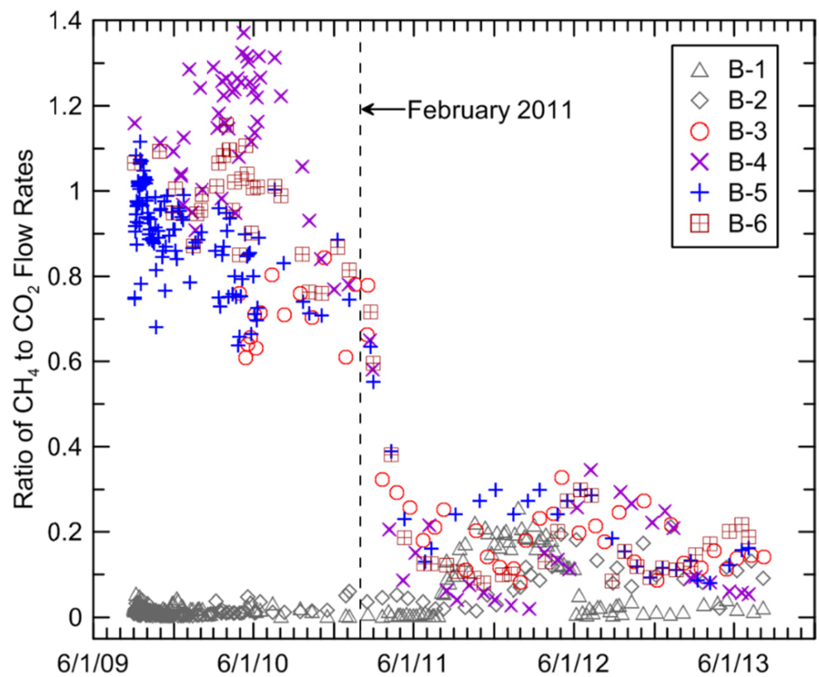


FIG 6. Trend of ratio of CH4 to CO2 flow rates along cross-section A-A' for gas extraction wells B-1 to B-6

Similar to the gas extraction well in Fig. 2, Fig. 7 shows that the decline in CH_4 to CO_2 ratio is accompanied by increased carbon monoxide and hydrogen levels. For example, Fig. 7(a) shows that carbon monoxide concentrations begin to increase at CH4 to CO2 ratio of 0.8. Carbon monoxide levels continue to increase from 500 to 8,000 ppmv for gas ratio values below 0.3. Fig. 7(b) shows that hydrogen levels are generally less than 8% v/v when the ratio of CH_4 and CO_2 is above unity. As the gas ratio decreases to 0.4, hydrogen levels continue to increase to ~36% v/v. Fig. 7(b) also indicates that hydrogen is present at CH_4 to CO_2 ratios above unity. However, the gas wellheads in Cell 4, which were not impacted by elevated temperatures, show no evidence of hydrogen gas. This indicates that the presence of hydrogen (e.g., > 1% v/v) when the ratio of CH_4 to CO_2 is above unity is a result of internal landfill gases mixing from elevated temperature and biodegradation areas. Therefore, hydrogen concentrations of about 35% v/v at low ratios of CH_4 and CO_2 in gas extraction wells

B-3 to B-6 are a consequence of elevated temperatures. Based on Fig. 6 and Fig. 7, landfill gas composition changes across the landfill to primarily carbon dioxide (60-80% v/v), hydrogen (10-35% v/v), and carbon monoxide (> 1,500 ppmv) during the movement/expansion of elevated temperatures.

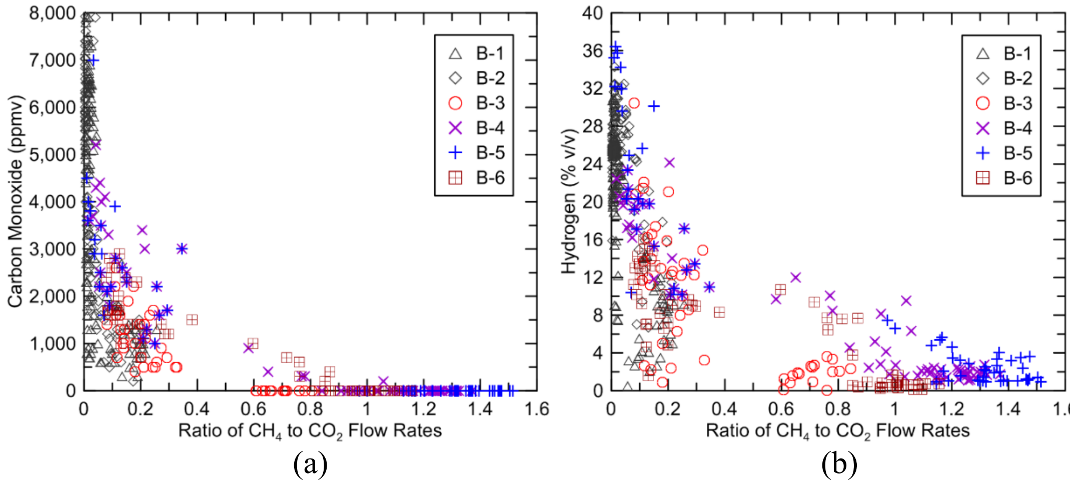


FIG 7. Gas extraction wells B-1 to B-6 trends for ratio of CH4 to CO2 flow rates with: (a) carbon monoxide and (b) hydrogen

Fig. 8 shows the cumulative settlement of two stability pins. One pin is located in Cell 5 and subjected to elevated temperatures while the other pin is in Cell 4, where normal anaerobic biodegradation prevails. The biodegradation pin shows that settlement for a 60 m waste height is about 1.3 m in ~1,300 days, which corresponds to a settlement rate ~0.5 m/yr. The Cell 5 pin initially settles at the same rate as the biodegradation pin. However, settlement begins to accelerate as the influence of elevated temperatures expands towards the stability pin. For example, vertical settlement is 0.5 m after an elapsed time of 800 days. By the end of the monitoring period, settlement is over 10 m. The corresponding settlement rate of 4.6 m/yr is about a magnitude higher (factor of ~9) than biodegradation. Fig. 8 also compares settlement with the ratio of CH_4 to CO_2 obtained from a gas extraction well located in the immediate vicinity of the Cell 5 pin. The ratio of CH_4 and CO_2 is above unity until time t= 600 days by which it declines to a ratio of ~0.35 in 50 days. The ratio gradually decreases to ~0.1 after t= 1,150 days. Before settlement transitions from normal biodegradation to an accelerated rate, the ratio of CH_4 to CO_2 decreased to values that indicate anaerobic processes are inhibited. Thus, Fig. 8 shows that rapid settlement occurs after methane composition decreases and is the delayed indicator of elevated landfill temperatures. During the time gap of ~200 days in which landfill gas is quickly changing composition, gas/leachate pressures and volume are increasing and are contributing to slope movement before the onset of excessive settlement. As a result, the case study discussed herein shows that the initiation and expansion of elevated temperatures results in a sequence of indicators that delineates the location, boundary, and movement.

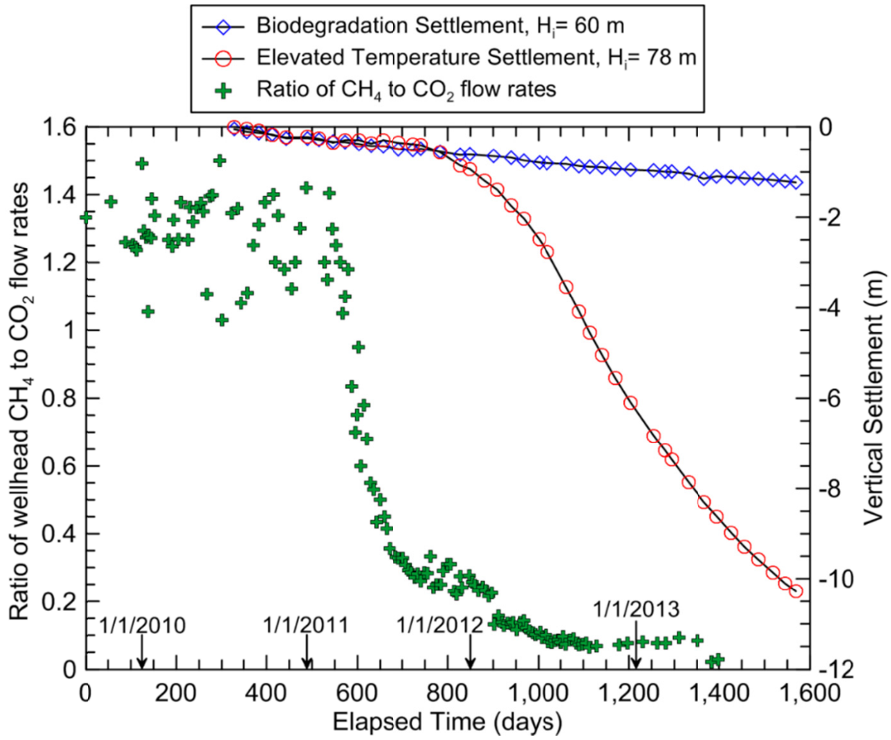


FIG 8. Comparison of elevated temperature and biodegradation settlement with timeline of decreasing ratio of CH4 to CO2 flow rates

SUMMARY AND RECOMMENDATIONS

Elevated temperature events can significantly impact the behavior and operation of a MSW landfill. If not addressed in an expedient manner, elevated temperatures can result in damage to the landfill infrastructure (i.e., gas extraction, leachate collection, and liner system), slope instability, and environmental conditions that adversely affect health and welfare of the local community. This paper presented a case study to identify the indicators of elevated temperatures and arrange these parameters into a chronological sequence, as follows:

(1) Changes in landfill gas composition, which are characterized by decreasing ratio of CH_4 to CO_2 flow rate ratios and elevated carbon monoxide and hydrogen levels (gas composition is found to advance in front of the elevated temperature region);
(2) Elevated waste and gas temperatures, e.g., wellhead temperatures increased from below the NSPS threshold of 55°C to 90°C;
(3) Elevated gas and leachate pressures, resulting in leachate outbreaks;
(4) Increased leachate volume and migration;
(5) Slope movement; and
(6) Unusual and rapid settlement.

Furthermore, during the expansion and/or migration of elevated temperatures, landfill gas changes quickly from predominantly methane (50-60% v/v) and carbon dioxide (40-55% v/v) to a composition of carbon dioxide (60-80% v/v), hydrogen (10-35% v/v), and carbon monoxide (> 1,500 ppmv).

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