Landfill Operational Techniques in the Presence of Elevated Temperatures

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Abstract

Elevated temperatures in municipal solid waste landfills can produce obnoxious odors, toxic gases, and aggressive leachates, as well as damage gas extraction, leachate collection, interim cover, and composite liner systems. They also can result in expensive remedial measures and warrant permanent closure of the facility. Several factors can lead to elevated landfill temperatures, including air ingress, partially extinguished surface fires, reactive wastes, and spontaneous oxidation. Landfills typically experience changes to gas composition and flow, leachate chemistry and volume generation, and surface movement. Based on observed management, operation, and maintenance of elevated temperature facilities, various operational techniques are proposed for isolating and containing the elevated temperatures in a landfill.

INTRODUCTION

Approximately 840 elevated landfill temperature incidents (surface and subsurface) 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; FEMA 2002). These events present a significant threat to the environment by releasing pungent odors (reduced sulfur compounds and organic acids), volatile organic compounds, benzene, and particulate matter (Nammari et al. 2004; Ruokojarvi et al. 1995; Lonnermark et al. 2008; Chrysikou et al. 2008). In addition, they can impact the integrity of the cover and liner systems, degrade leachate quality and gas composition, and induce slope instability and excessive settlement (Lewicki 1999; Jafari et al. 2014; Stark et al. 2012; Øygard et al. 2005).

Under normal conditions, the temperature of the waste mass and landfill gas generated by a MSW landfill usually ranges between 30 and 65°C during anaerobic decomposition. Landfill gas is composed mostly of methane (CH_4= 45–60% v/v) and carbon dioxide (CO_2= 40–60% v/v) in approximately equal amounts, with <3% v/v nitrogen (N_2), <1.5% v/v oxygen (O_2), <1% v/v hydrogen (H_2), and trace concentrations of carbon monoxide (CO) (Martin et al. 2013). With respect to carbon monoxide, concentrations in gas generated by normally operating landfill facilities do not exceed 20 ppmv (ATSDR 2001), and concentrations exceeding 1,000 ppmv are indicative of subsurface combustion (FEMA 2002). Landfills does not exhibit anomalously high gas pressures (>0.5 kPa) or flow rates, which could be an indication of abnormal activity. Evidence of flame, smoke, rapid, and excessive settlement suggests active thermal breakdown of waste and are not present under normal operating conditions (Martin et al. 2013). Table 1 presents a summary of operating conditions at MSW landfill under normal operating conditions.

Table 1.Summary of MSW landfill parameters for normal anaerobic decomposition conditions (from Martin et al., 2013).

MSW landfill monitoring parameters	Normal operating conditions
Gas extraction system	
Gas wellhead temperature	<65°C[a]
Gas pressure (kPa)	<0.5[b] (bioreactors 0.5-16)
Methane (v/v%)	45–60[c]
Carbon dioxide (v/v%)	40–60[c]
Carbon monoxide (ppmv)	<20[c]
Hydrogen (v/v%)	<1[c]
Waste mass	
Waste temperature	30–65°C[a]
Landfill settlement (% of initial height)	5–10

[a]U.S. EPA (2006)
[b]Young (1989); Hettiarachchi et al. (2007).
[c]Agency for Toxic Substances and Disease Registry (2001).

There are many possible mechanisms and combinations of landfill operations and waste type that can cause temperatures to elevate from normal conditions, i.e., temperatures above which anaerobic decomposition is usually curtailed (Farquhar and Rovers 1973; McBean et al. 1995). A few examples include air intrusion, partially extinguished surface fires, disposal of reactive wastes (incinerator ash, aluminum dross, and magnesium chloride), spontaneous oxidation, and smoldering combustion (i.e., oxidation reaction occurring in the solid phase that results in the release of heat, gas, and solid products). A major contributor is the introduction of ambient air into a landfill during gas collection and control operations and/or poor interim soil or geosynthetic cover maintenance. The introduction of oxygen creates aerobic conditions that can increase waste temperatures to 85°C and higher if smoldering combustion develops.

PROGRESSION OF INDICATORS

Based on observations from large-scale, multi-year landfill case studies, Stark et al. (2012) and Jafari (2015) indicate the expansion of elevated temperatures from a localized area progresses as follows: (1) decreased methane to carbon dioxide flow rate ratio with subsequent increase generation and accumulation of carbon monoxide and hydrogen 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 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. For example, Figure 1 shows the relationship between increasing wellhead temperature and changes in the ratio of CH_4 to CO_2, hydrogen levels, and carbon monoxide concentrations for a single gas extraction well at a facility experiencing an elevated landfill temperature event (ELTE). Landfill gas was initially 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 microbial activity prior to the ELTE (Powell et al. 2006; Barlaz et al. 2010; Martin et al. 2013). 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.

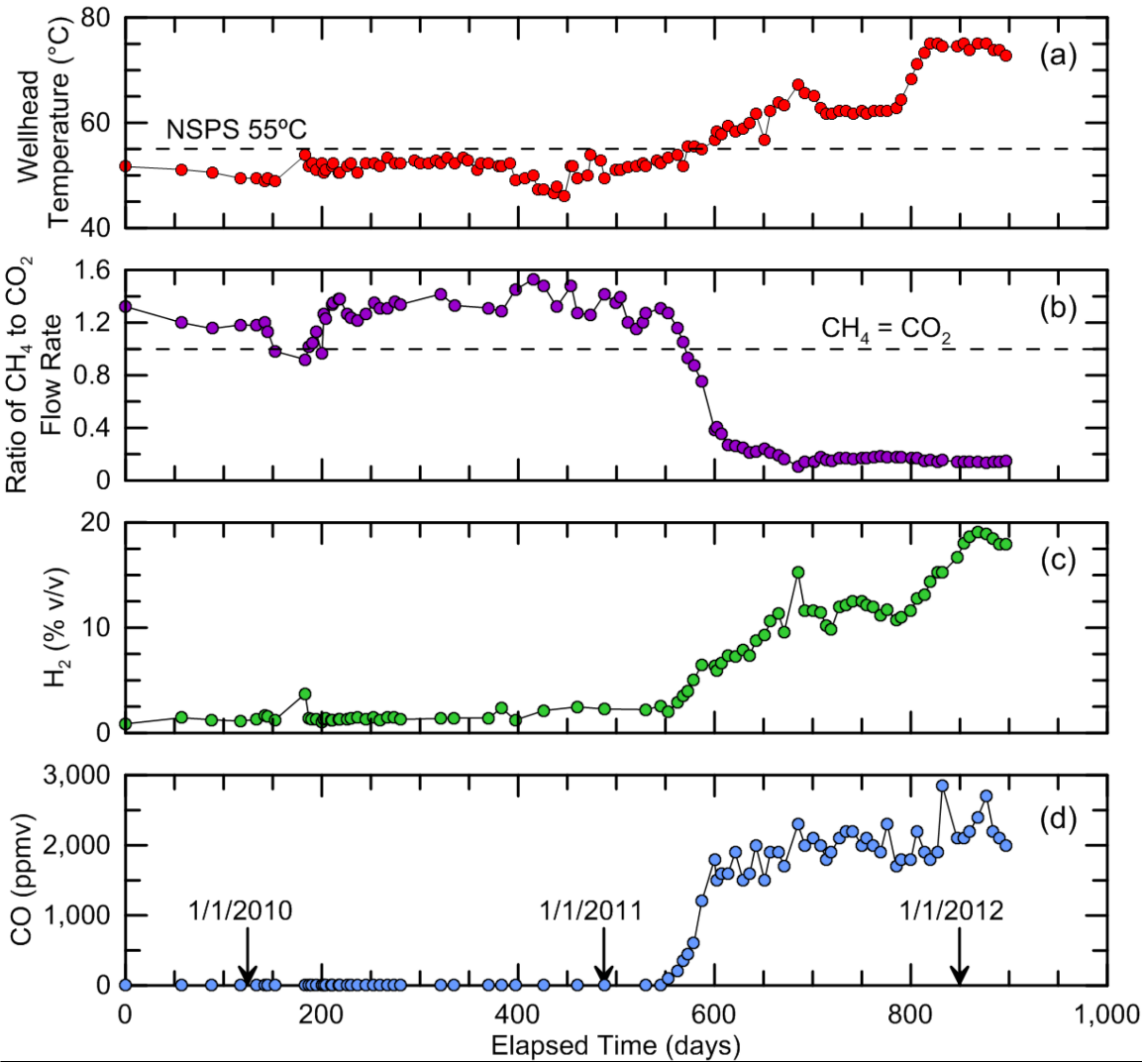


Figure 1. Gas extraction well trends: (a) temperature, (b) ratio of CH_4 to CO_2 flow rate, (c) hydrogen and (d) carbon monoxide.

In Figure 1(a), the gas extraction well (GEW) is operating under normal conditions because wellhead temperatures are below the NSPS limit of 55°C and the ratio of CH_4 to CO_2 is greater than unity (see Figure 1(b)). This represents the control conditions of the facility before initiation of elevated temperatures. The gas composition remains 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 only 50 days (time = 600 days). Wellhead temperatures exceeded the NSPS threshold of 55°C at a 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 waste. For example, heat conduction caused by only a thermal gradient is a slower process than convection and advection of gas to an extraction well, so the increasing temperature trend occurs after the gas was removed. This observation suggests that changes in gas composition can occur in advance of the heating front, with increasing wellhead temperatures being an indication of the approaching smoldering front. Hydrogen levels were < 2% v/v and carbon monoxide (CO) was not measured when the ratios of CH4 to CO2 remained above unity. Figure 1(c) shows that hydrogen increased at t= 550 days to a maximum concentration of 20% v/v. Similar to hydrogen, 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 Figure 1(b) to (d), it is evident that changes in the ratio of CH_4 to CO_2, hydrogen, and CO occur nearly at the same time and precede a rise of gas wellhead temperature (see Figure 1a). Moreover, the ratio of CH_4 to CO_2 and CO are characterized by rapid changes while hydrogen increase occurs at a slower pace, similar to wellhead temperature changes.

Figure 2 shows the cumulative settlement of two stability pins, i.e., a survey stake or hub, were anchored in the cover soil below the geomembrane cover and used to monitor changes in northing, easting, and elevation. One pin is located in an area where an ELTE is occurring while the other pin is in area that has not been impacted by elevated temperatures, where normal anaerobic biodegradation still prevails. The biodegradation pin shows settlement for a 60 m thick waste area is only about 1.3 m in ~1,300 days, which corresponds to a strain rate of about 0.6 %/yr. The ETLE pin initially settles at the same rate as the biodegradation pin. However, settlement accelerates as the influence of elevated temperatures expand towards the stability pin. For example, vertical settlement is 0.5 m at an elapsed time of 800 days. By the end of the monitoring period, settlement is slightly over 10 m at t = 1,600 days. The corresponding strain rate of 5.7 %/yr is about 9.5 times greater than biodegradation. Figure 2 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 ETLE 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, Figure 2 shows that rapid settlement occurs after methane concentration decreases and is a delayed indicator of elevated landfill temperatures. During the time gap of about 200 days in which landfill gas is quickly changing composition, gas and leachate pressure increase and migration are contributing to slope movement before the onset of excessive settlement.

RECOMMENDATIONS FOR LANDFILL OPERATORS

Tables 2 and 3 provide recommendations in conjunction with the landfill classification zones described above so landfill operators can identify the progression of elevated temperatures in a landfill and develop an operational response. When wellhead temperatures increase above 55°C (131°F) and damage to the wellhead and/or cracks in the cover system are observed, the landfill operator typically applies to the state regulatory agency for Higher Operating Variances (HOVs) for each gas wellhead. HOVs allow the landfill operator to show that methane production is not inhibited at elevated wellhead temperatures (~65°C; ~150°F). During the HOV period, monitoring frequency of oxygen levels (< 5% v/v), wellhead vacuum (< 0 inches water column), and gas temperature should be increased. Increased public complaints are usually attributed to odors emanating from the cracks in the cover system and/or leaks around gas wells.

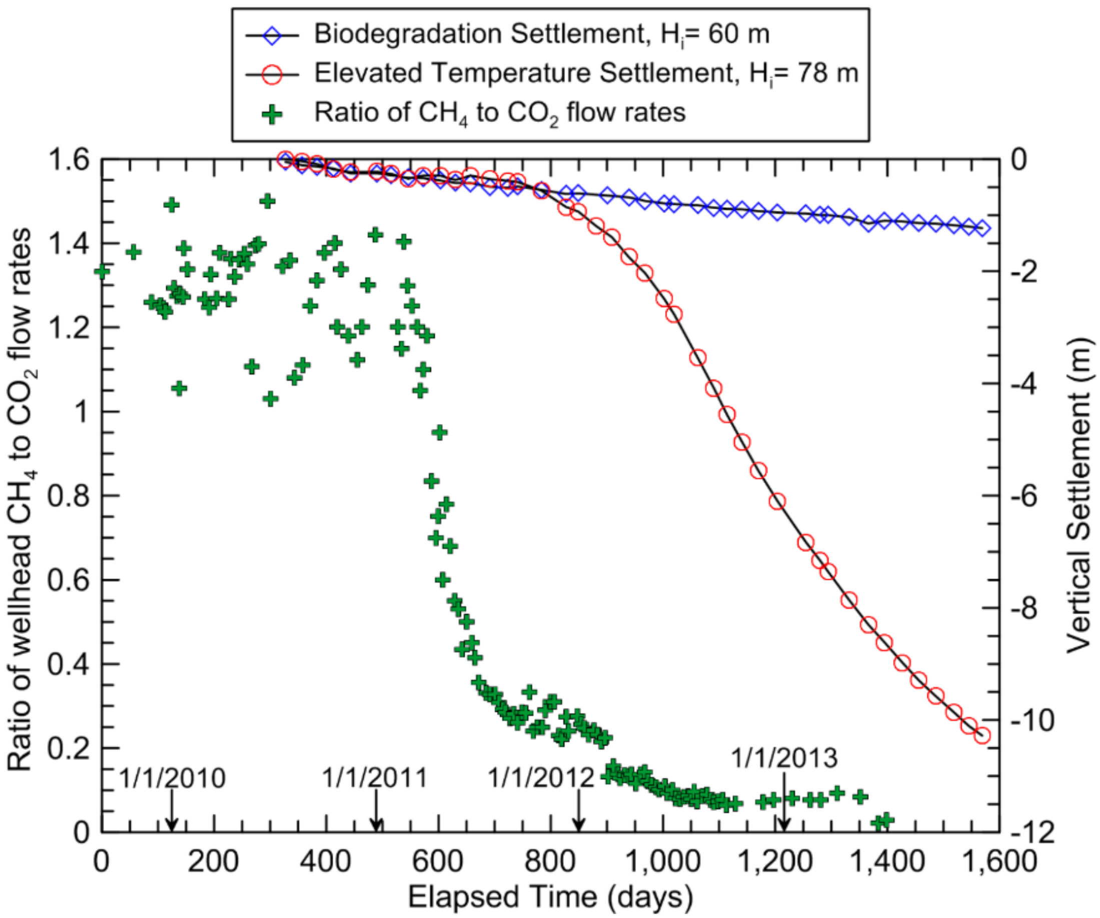


Figure 2. Comparison of elevated temperature and biodegradation settlement with timeline for decreasing ratio of CH_4 to CO_2 flow rates.

Under the HOV permit, the landfill operator is usually tasked to ensure cover system integrity, expand the capabilities of the gas extraction and collection system (increase number of wells, install high temperature resistant wellhead pipe materials and pump equipment, and remove condensate in the header lines), and install odor neutralizers to combat foul odors and possible air intrusion. In addition, combustion residue in gas well pipes may accumulate. As the landfill gas composition changes, hydrogen gas can reduce flare combustion efficiency and corrode integral parts of the flare system. When elevated gas pressures and flow cause liquid outbreaks, the operator is recommended to place additional soil cover or install a temporary exposed geomembrane cover.

Leachate generated from elevated temperatures typically changes from a pale brown to black color, contains high concentrations of particulates, and resembles an oil-like consistency. The facility operator may be required to construct a pre-treatment plant on-site to address the contaminants in the leachate before transporting it off-site. Indicators of slope instability include tension cracks in the soil cover, toe bulging, and possible tilted or pinched gas wellheads. For affected slopes, a toe buttress can be constructed to balance the driving and resisting forces, and a slope monitoring system installed to monitor rate and magnitude of slope movement due to elevated temperatures.

Rapid settlement can cause large drops in landfill height, which can tear the geomembrane cover system. It is imperative that the landfill operator monitor the integrity of the soil cover or geomembrane to prevent air intrusion. However, the geomembrane cover also limits visual observations of smoke or steam, desiccated cover soil, leachate outbreaks, and slope behavior. To isolate and contain the ETLE, one alternative is to excavate waste to create an air break between the impacted region and the rest of the facility. Other possible techniques to reduce the effect of ETLEs include passive elements, e.g., a concrete/soil mix vertical curtain wall that acts as a heat conduction barrier, or active elements, e.g., injection of N_2 or CO_2 and ground heat exchangers.

Table 2. Progression of indicators linked to field observations.

Progression of Indicators	Field Observations
Changes in gas composition	Odors; possible combustion residue in GEW, air intrusion, and flare corrosion
Elevated gas and waste temperatures	GEW temps >55°C; damaged GEW pipe and pump; cracked soil cover
Increased gas pressure and flow	Leachate and gas outbreaks
Leachate outbreaks and increased volume	Leachate black oil-like consistency; moisture in GEWs and lateral headers
Possible slope instability	Tension cracks in soil cover; toe bulging; tilted GEWs
Unusual settlement	Crater or settlement bowl in landfill develops

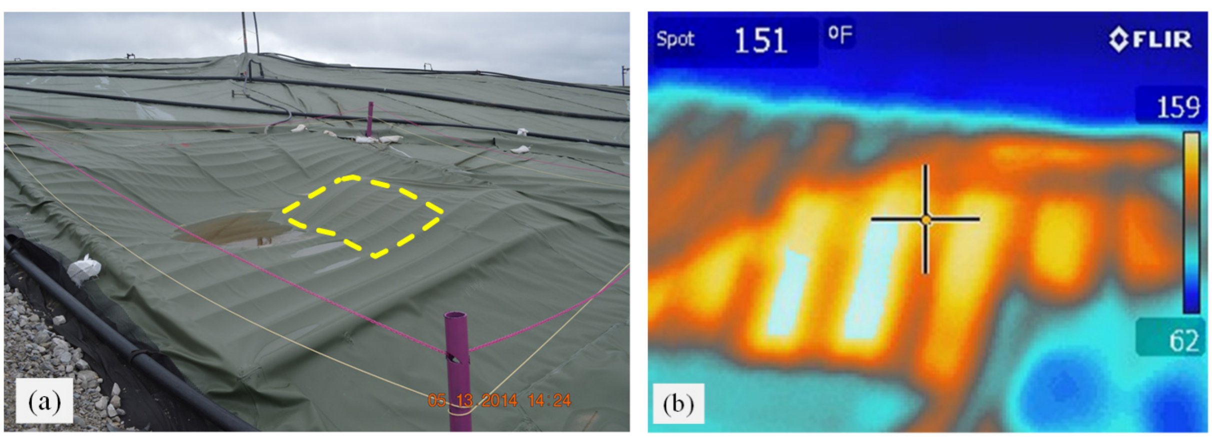
Table 3. Recommendations for landfill operators after observing elevated temperature indicators.

Progression of Indicators	Possible Actions
Changes in gas composition	Ensure soil cover integrity; increase GEWs & flare capacity
Elevated gas and waste temperatures	Repair GEW; maintain soil cover integrity; obtain HOVs; reduce vacuum to GEW; increase number of GEWs
Increased gas pressure and flow	Install additional soil or temporary geomembrane cover; install GEWs or trenches along waste edges
Leachate outbreaks and increased volume	Collect, transport, and treat leachate; remove liquid in GEW pipes; install new leachate collection sumps and pipes
Possible slope instability	Construct toe buttress; install slope monitoring system
Unusual settlement	Repair cracks and rills in soil cover and rips/tears in geomembrane cover; maintain cover integrity

INFRARED IMAGERY

A technology to rapidly and remotely identify surface elevated temperatures is thermal infrared (TIR) imaging. An example of infrared thermography using FLIR® E33 and a FLIR® K50 infrared cameras at an ETLE site is shown in Figure 3. Figure 3(a) shows an area of localized settlement due to the ETLE. The yellow dashed rectangle in Figure 3(a) corresponds to the infrared image shown in Figure 3(b). The TIR imagery shows elevated temperatures in the area of localized settlement. The maximum surface temperature measured in this area is about 70°C, which indicates the ETLE may be close to the surface. The infrared imagery was corroborated by nearby gas wellhead temperatures of ~85°C. As a result, of the elevated temperatures, the area was cordoned off with purple poles (see Figure 3 (a)) for safety precautions. The areas immediately outside the hot spot represented by teal and dark blue colors (temperatures <38°C) in Figure 3(b) are less affected by the migrating smoldering event.

The photographs in Figure 3 suggest infrared thermography can be used to locate nascent hot spots in the gas and temperature fronts. TIR can also measure surface radiant energy as temperatures, which tend to be lower than subsurface temperatures (Martin et al. 2013) but are still useful in assessing combustion presence and movement, and providing spatial and temporal changes below geomembranes and other landfill covers. Measured surface temperatures in the ETLE front can be used to evaluate the integrity of the geomembrane and determine if repair/maintenance is required to minimize odors and toxic gas releases. Images of gas extraction wells and panoramic views of landfill slopes are also being used to identify hot spots. The access to real time TIR imagery is critical to landfill personnel, technicians, and consultants and first responders to safely monitor landfills to evaluate indicators, observations, and remedial measures in Tables 2 and 3.



(a) (b)

Figure 3. Image of Site 2 geomembrane using: (a) digital camera and (b) infrared thermography.

SUMMARY

Elevated temperatures above the NSPS threshold 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 landfill infrastructure, e.g., gas extraction, leachate collection, and bottom liner system), slope instability, and environmental conditions that adversely affect health and welfare of the local community. This paper summarizes the main indicators of elevated temperatures and arranges them in the following chronological sequence: (1) changes in landfill gas composition; (2) elevated waste and gas temperatures; (3) elevated gas and leachate pressures; (4) increased leachate migration; (5) slope movement; and (6) rapid and unusual settlement. These indicators were related to field observations and possible remedial measures based on experience from multiple, large-scale ELTEs. A technique using thermal infrared imagery is proposed to monitor development of elevated temperatures at the surface, evaluate the performance of the geomembrane cover liner, and assist in identifying hot gas extraction wells.

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