

Service Life of HDPE Geomembranes Subjected to Elevated Temperatures

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Abstract: Subtitle D landfills may experience elevated temperatures for a variety of reasons such as hydration of combustion ash, waste biodegradation with and without leachate recirculation, aluminum production waste and combustion ash reactions, and wastes received with elevated temperature. Elevated temperatures can reduce service life or effectiveness of high density polyethylene (HDPE) geomembranes by accelerating antioxidant depletion of geomembranes and polymer degradation. A case history is presented to illustrate the potential effects of elevated temperatures and time-temperature history on a HDPE geomembrane and the associated reduction in service life or effectiveness. The geomembrane service life was influenced by the peak temperature, e.g., 60–80°C, the duration of peak temperatures (time-temperature history), and the time to complete antioxidant depletion. This paper also discusses possible criteria for assessing the service life of geomembranes, such as applicable engineering properties, locations for service life assessments, definitions of geomembrane service life, and measures that could be adopted if service life were reduced significantly. DOI: 10.1061/(ASCE)HZ.2153-5515.0000188. © 2014 American Society of Civil Engineers.

Author keywords: Aluminum; Dross; Heat generation; Exothermic chemical reaction; Landfill fire; Landfill gas; Elevated temperature; Geomembranes; Geosynthetics; Durability; Waste disposal; Service life; Municipal solid waste.

Introduction

Municipal solid waste (MSW) placement facilities are required to have a barrier system to control the escape of contaminants from the waste to groundwater or surface water bodies to negligible levels. Landfill temperature is important because it can affect the performance of various barrier system components, such as the geomembrane (GMB), low hydraulic conductivity compacted soil liner (LHCSL), geotextiles (GTXs), geonet drainage component (GDC), and geosynthetic clay liner (GCL). Elevated temperatures can reduce the service life of geomembranes, LHCSLs, and GCLs (Rowe 2005) in both single and double composite liner systems (Southen and Rowe 2004, 2005a, b, 2011; Rowe 2005, 2012; Rowe et al. 2008, 2009, 2010; Rowe and Hoor 2009; Azad et al. 2011, 2012; Hoor and Rowe 2013).

Landfill monitoring shows that heat generated by MSW decomposition, hydration of combustion ash, and aluminum production waste and combustion ash reactions can significantly increase the temperature at the underlying liner system. Liner system

temperatures of 30–40°C can be expected (Klein et al. 2001; Yoshida and Rowe 2003; Rowe et al. 2004; Rowe 2005; Koerner and Koerner 2006; Koerner et al. 2008; Yesiller et al. 2005; Hanson et al. 2005, 2008, 2010; Rowe and Islam 2009; Rowe 2012), and in some cases temperatures up to 80°C have been measured (Calder and Stark 2010; Stark et al. 2011; Martin et al. 2013). The heat generated by a waste containment facility is a function of waste accepted management practice (e.g., leachate recirculation and gas system operation) and the nature of the waste degradation process. For instance, Brune et al. (1991) reported that an increased rate of waste placement correlated with an increased rate of temperature increase. Available moisture can accelerate the rate of temperature increase and temperature in a landfill by increasing the rate of waste degradation (Rowe 2005).

Heat Generation in Landfills

With the interest in waste to energy [e.g., methane generation, disposal of aluminum production waste (APW), combustion of MSW for energy and to reduce waste volume, bioreactors, interest in covering landfills for aesthetic and solar panel purposes, and acceleration of decomposition via leachate recirculation), temperatures in landfills are increasing and causing increased temperatures at the liner system. The biodegradation of MSW or the heat of hydration of incinerated bottom ash are the primary factors contributing to the generation of heat in landfills (Klein et al. 2001; Yoshida and Rowe 2003; Rowe 2005; Yesiller et al. 2005; Koerner et al. 2008). More recently, APW and incineration and combustion ash-related reactions can generate temperatures up to 150°C (300°F) (Calder and Stark 2010; Stark et al. 2011), which can become problematic for landfill operations.

The U.S. DOE (1999) estimates that at least 1 million metric tons (approximately 1.1 million tons) of APW are placed annually in Resource Conservation and Recovery Act (RCRA) Subtitle D landfills. These waste materials contain variable amounts of

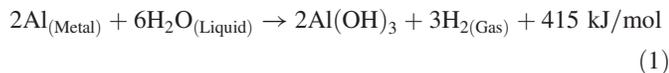
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Note. This manuscript was submitted on April 26, 2012; approved on February 7, 2013; published online on February 9, 2013. Discussion period open until June 1, 2014; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Hazardous, Toxic, and Radioactive Waste*, Vol. 18, No. 1, January 1, 2014. © ASCE, ISSN 2153-5493/2014/1-16-26/\$25.00.

aluminum metal and aluminum compounds, such as aluminum carbide, aluminum nitride, aluminum sulfide, and aluminum oxides, mixed with sodium and potassium salts and other substances (Manfredi et al. 1997; Shinzato and Hypolito 2005; Szczygielski 2007) that can react with available moisture. The most likely heat-generating reaction of APWs in a Subtitle D landfill or non-hazardous industrial landfill involves the amphoteric reaction of aluminum metal with water (Calder and Stark 2010) as follows:



These reactions can release large amounts of heat and possibly flammable hydrogen gas in waste. Internal temperatures of waste masses undergoing this reaction have been observed between 88°C (170°F) and 110°C (230°F), at which desirable microbial activity is terminated and corresponding methane production is severely curtailed. Fig. 1 shows an example of two gas wells in an APW monofill in Ohio where downhole temperatures were measured at 3 and 7.6 m below the ground surface. At a depth of 7.6 m, the maximum temperature increases to 112°C within the first 50 days after disposal and gradually decreases thereafter. The maximum temperatures measured at a depth of 3 m is 108°C, but the average trend line from both gas wells indicate that the maximum temperature produced is more likely between 80 and 90°C. Lower temperatures are observed in Fig. 1(a) due to heat loss to the surface. These exothermic reactions and associated changes in gas composition and increased gas pressure also usually cause intense nuisance odors (e.g., ammonia) and possible combustion of surrounding MSW.

The temperature in APW landfills depends on both the availability of liquids and free metallic aluminum. Whereas the maximum temperature in MSW landfills is located within the center to middle third fraction of the depth of the waste, the maximum temperature in APW landfills depends on the location of APW and amount of metallic aluminum reacted in Reaction (1).

For MSW landfills, waste decomposition temperatures near the base of the MSW cells and in the liner systems are relatively steady and are elevated above ground temperature but below the maximum values in the central zones of the landfill.

Effect of Temperature on HDPE Geomembranes

Due to space constraints, this paper focuses on the effects of elevated temperature on the geomembrane and omits discussion about the GCL, GTXs, geonets, and LHCSLs. This section further focuses on the effect of elevated temperatures on the performance of high-density polyethylene (HDPE) geomembranes. The focus is on HDPE geomembranes, as opposed to some other geomembrane type, because they are most frequently used for the geomembrane component of a composite liner system in Subtitle C (hazardous waste) and Subtitle D (MSW) landfills.

Manufacturers of HDPE geomembranes do not recommend sustained temperatures greater than 57°C (160°F) for HDPE and 46°C (140°F) for linear low-density polyethylene (LLDPE), which are primarily used for final cover systems and not composite liner systems (Yazdani, personal communication, 2005). Elevated temperatures can accelerate the depletion of antioxidants added during the geomembrane manufacturing process and accelerate subsequent oxidation of the polymer, leading to a loss in stress crack resistance and a decrease in geomembrane service life (Rowe et al. 2009, 2010).

HDPE geomembranes consist of, by weight percentage, 96–97% polyethylene resin, 2–3% carbon black, and approximately 0.5–1% antioxidants (Hsuan and Koerner 1998). Antioxidants are added to HDPE geomembrane formulations to reduce polymer degradation during processing and oxidation reactions during the initial stage of geomembrane service life (Hsuan and Koerner 1998). The degradation of HDPE geomembranes has been examined by a number of researchers (Hsuan and Koerner 1998; Sangam and Rowe 2002; Müller and Jacob 2003; Tarnowski et al. 2005; Needham et al. 2006; Jeon et al. 2008; Rowe 2005;

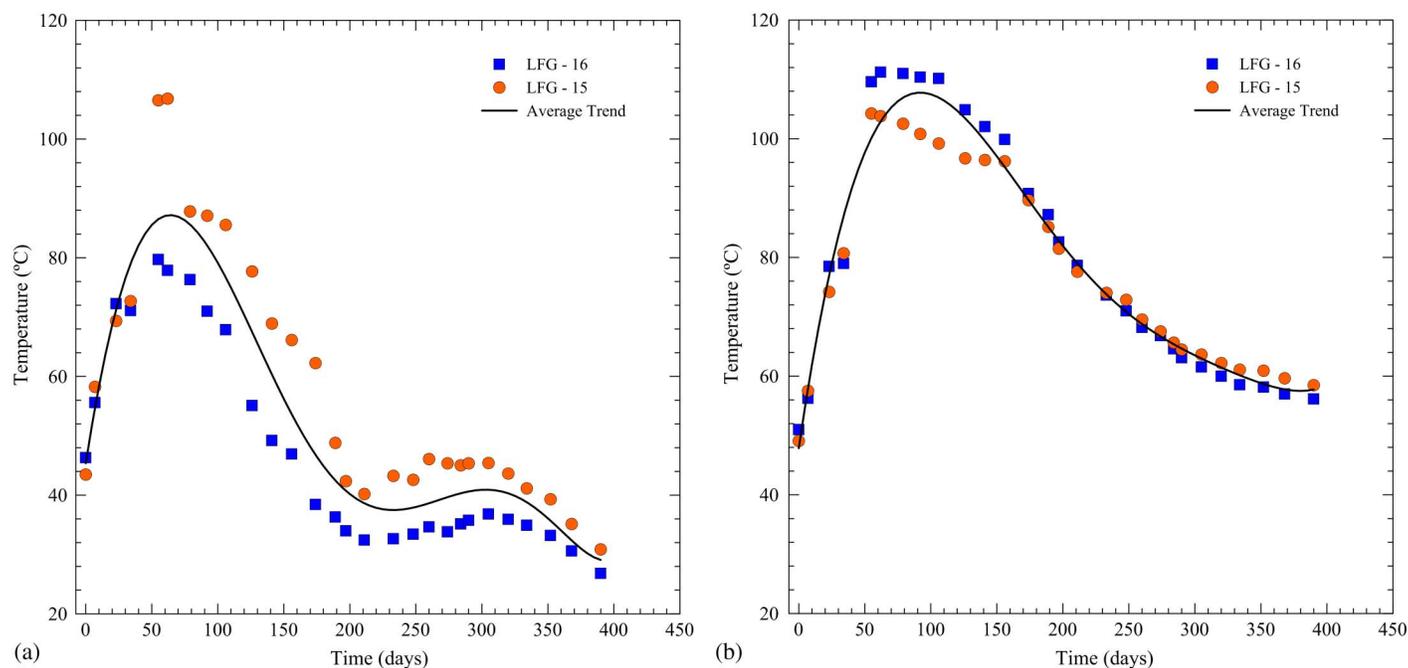


Fig. 1. Maximum temperatures of APW monofill: (a) depth 3 m; (b) depth 7.6 m

Table 1. Estimated HDPE Geomembrane Service Life Based on 50% Reduction in Tensile Strength at Break for Different Temperatures [Based on Rowe (2005)]

Temperature (°C)	Service life (years)
20	565–900
30	205–315
35	130–190
40	80–120
50	35–50
60	15–20

Rowe and Rimal 2008a, b; Rowe et al. 2008, 2009, 2010; Rimal and Rowe 2009) and is generally considered to consist of the following three stages: (Stage A) depletion of antioxidants; (Stage B) induction or start of polymer degradation; and (Stage C) polymer degradation and decrease in key physical properties (Hsuan and Koerner 1998).

During Stage A, antioxidants present in the geomembrane are progressively volatilized, diffused, or oxidized (Koerner 1998). The duration of Stage A is important because the active antioxidants protect the geomembrane polymer from degradation. During Stage B, polymer degradation commences but there is no measurable change in geomembrane engineering properties, even though the antioxidants have been significantly reduced or removed (Koerner 1998). Induction of polymer degradation continues in Stage B until the effects of the oxidation-induced scission of polyethylene chains becomes measurable (Koerner 1998). During Stage C, measurable changes in the engineering properties of the geomembrane occur (Koerner 1998) until the service life of the geomembrane is reached. The duration of each of the three stages is referred to as depletion time (Stage A), induction time (Stage B), and degradation time (Stage C), respectively. The service life of a geomembrane is the sum of the duration of these three stages. Table 1 provides the service life of HDPE geomembranes subject to temperatures of 20 to 60°C in a laboratory-simulated landfill liner system (Rowe 2005) using 50% reduction in the tensile strength at break as the end of service life.

Fig. 2 shows the decrease in service life with increasing temperature. Only the results for Stage A, or antioxidant depletion, are based on laboratory testing that simulates landfill disposal conditions. Stages B and C degradation are based on polyethylene pipe test results presented by Viebke et al. (1994). Although the estimated service life values assume a constant temperature, even a short duration of elevated temperature can significantly reduce HDPE geomembrane service life to several decades (Fig. 2) and, by extrapolation, to as little as a few years at higher temperatures (Rowe and Islam 2009).

Elevated Temperature Case History

The effects of elevated temperatures on a Subtitle D-compliant composite liner system are illustrated using a case history and some of the liner system issues that can develop when a facility experiences elevated temperatures. This case is described in detail by Stark et al. (2011), so only a brief review is provided herein. The facility accepted between 540,000 metric tons (600,000 tons) and 1,030,000 metric tons (562,000 tons) of aluminum production waste (mostly black dross or salt cake) from 1991 through 2004. According to the March 2007 Findings and Orders issued by the Ohio EPA, from 1993 to 2006 the facility placed the aluminum production wastes (mostly black dross or salt cake) in Cells 1, 3, 4, and 6A (Fig. 3). Around 2005, it became obvious that the facility

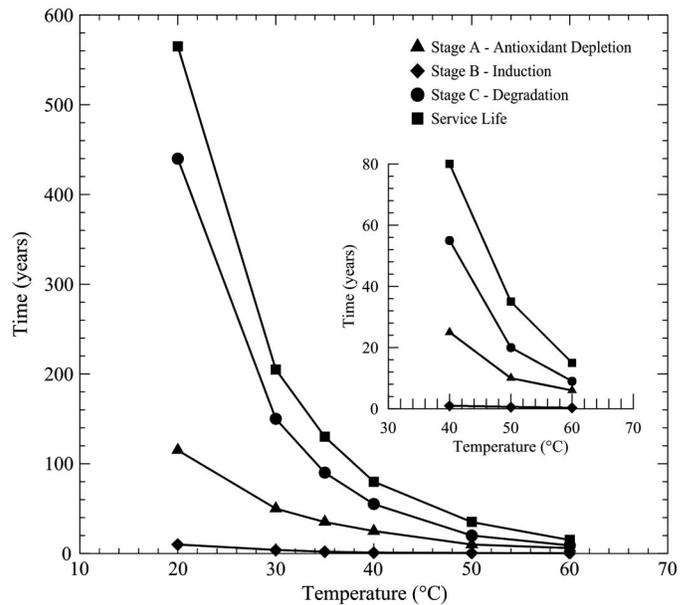


Fig. 2. Duration of degradation Stages A–C and total service life based on 50% reduction in tensile strength at break [data from Rowe (2005)]

was experiencing an abnormal reaction because of the extremely bad odors, elevated temperatures, increased gas and liquid pressures, and rapid settlement of the waste. Based on observations and gas and leachate compositions, it was concluded that an exothermic aluminum reaction was occurring and generating considerable heat. Fig. 4 illustrates increasing gas wellhead temperatures from April 2006 to December 2007. It is evident that between April 2006 and December 2006, temperatures increased to approximately 100°C in Cells 3, 4, and 6A. However, Cells 1 and 2 did not exhibit elevated temperatures above 55°C because the haul road (Fig. 4, black line) used by disposal trucks to reach the working face of the landfill acted as a thermal barrier and prevented heat from spreading to Cells 1 and 2.

At this site, the composite liner system consists of a single composite liner system with the following components in Cells 1–4:

- 0.3 m (1 ft) leachate collection system washed sand (Cell 1) or pea gravel (Cells 2–4),
- 400 g/m² (12 oz/yd²) to 540 g/m² (16 oz/yd²) protective nonwoven geotextile,

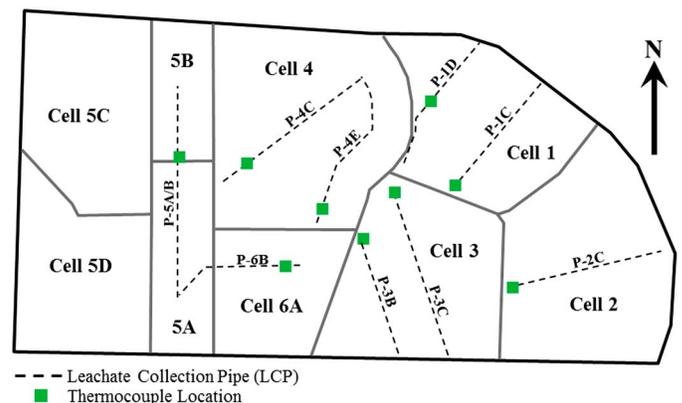


Fig. 3. Sketch of Cells 1–6 and thermocouple locations

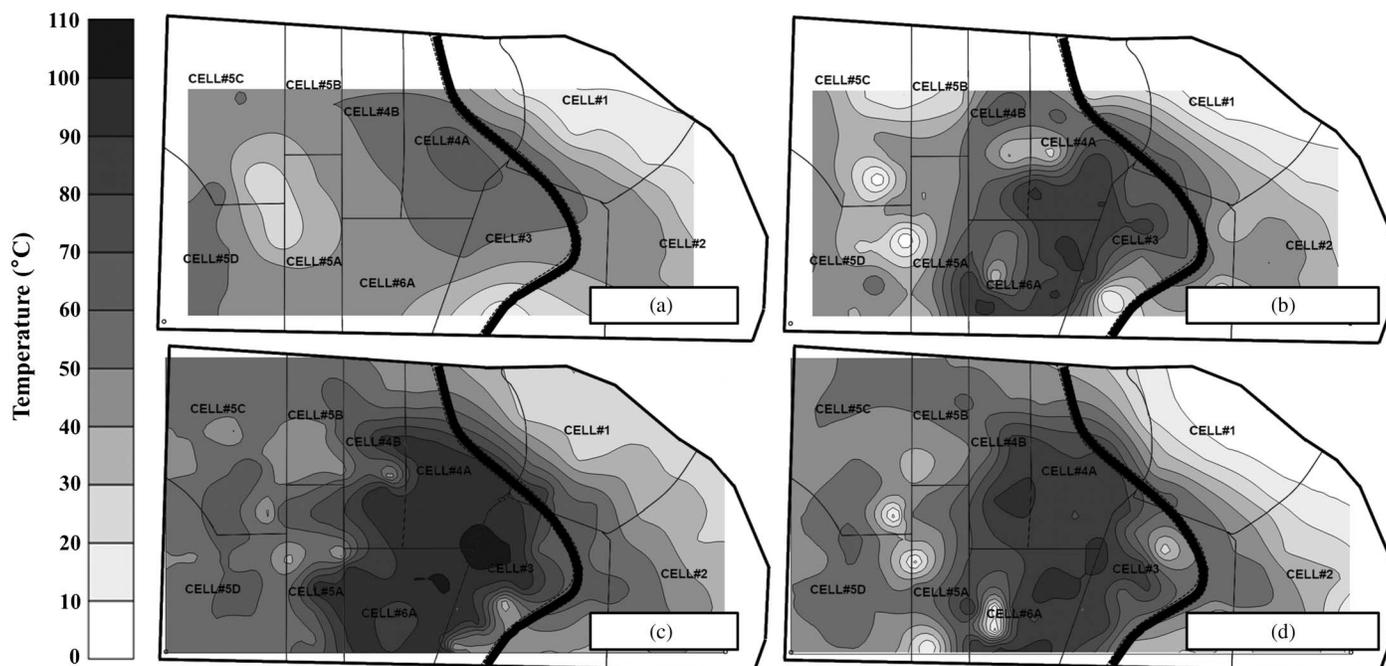


Fig. 4. Gas well head temperatures

- 1.5 mm (60 mil) HDPE geomembrane,
 - 1.5 m (5 ft) low hydraulic conductivity soil liner (LHCSL).
- In Cells 5A–5D and Cell 6, the composite liner system consists of the following components:
- 0.3 m (1 ft) leachate collection system pea gravel (Cells 5D, 6) or 0.45 m (1.5 ft) shredded tires (Cell 5A–5C),
 - 270 g/m² (12 oz/yd²) to 540 g/m² (16 oz/yd²) protective nonwoven geotextile,
 - 1.5 mm (60 mil) HDPE geomembrane,
 - needle-punched reinforced geosynthetic clay liner (GCL), and
 - 0.9 m (3 ft) low hydraulic conductivity soil liner (LHCSL).

In May 2007, the facility installed thermistors in the leachate collection pipes (LCPs; Fig. 3 for locations of thermocouples) to monitor temperature conditions at the geomembrane in the single composite liner system. The measured temperatures shown in Fig. 5 exceed 70°C (176°F) at LCP 3B, 3C, and 4E and are sustained for the entire monitoring period. Temperatures between 38 and 44°C were measured at LCP 1C and 2C. Temperatures at LCP 5A/B and 4C started at 40°C but increased during the monitoring period to 60°C, a result of the APW reaction expanding to the west. Given the sustained elevated temperatures, the integrity of the HDPE geomembrane was investigated.

Idealized Temperature Variation in a Landfill

To predict the service life of a HDPE geomembrane, it is necessary to assume an idealized temperature variation with time (Fig. 6). The temperature at the base of the landfill is assumed to start at T_o (typical ground temperature in the absence of landfilling) and remains constant until a time t_1 . The temperature then increases linearly to an intermediate value of T_i (due to waste decomposition) at time t_2 and remains constant until a time t_3 . The temperature increases again linearly to a peak value of T_p (due to, e.g., exothermic reaction or smoldering combustion) at time t_4 and remains constant until a time t_5 . After time t_5 , the temperature decreases linearly and reaches the initial ground temperature T_o at time t_6 and remains constant thereafter.

Table 2 summarizes six idealized landfill liner time-temperature histories based on data from Fig. 5. Cases 1 and 2 simulate LCP 1C and 2C (located in Cells 1 and 2 away from the APW reaction). They represent geomembrane service life for normal MSW landfills. Cases 3–6 evaluate the effect of peak temperatures on the geomembrane service life. As an example, Fig. 6 illustrates the liner time-temperature history for Case 6 in the context of the timeline of landfill operations. Permitted in 1991, the facility operated as a dry cell (no leachate recirculation) for the first 5 years. In April 1996, leachate recirculation began and continued until 2006, when the ongoing exothermic reaction between APW and recirculated leachate became obvious in Cells 3, 4, and 6A. As a result, the initial temperature T_o is assumed to start at 20°C and to remain constant for 5 years (until 1996). After leachate recirculation commences,

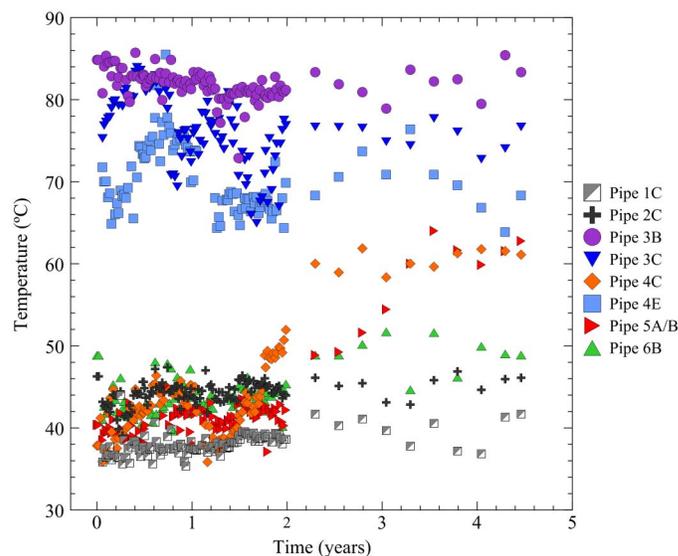


Fig. 5. Leachate collection system temperatures as a function of time

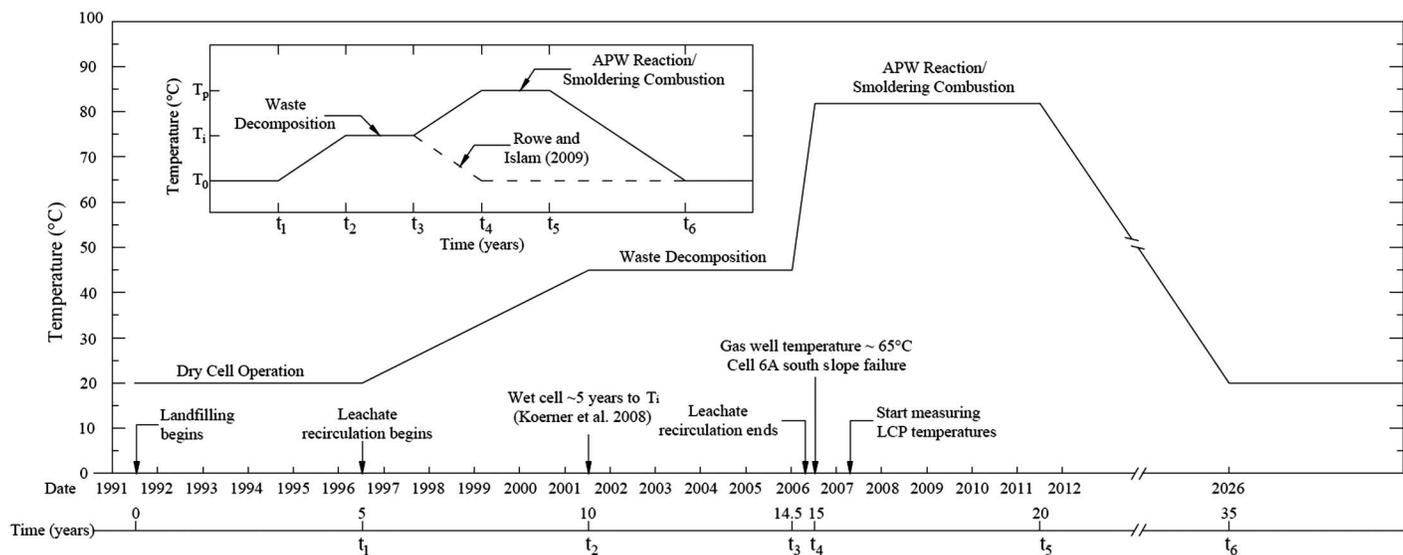


Fig. 6. Idealized temperature variation with time in a landfill under elevated temperatures

accelerated waste biodegradation causes temperatures to reach T_i (35 to 45°C in Fig. 5). Koerner et al. (2008) monitored the temperatures on the primary geomembrane at two landfill cells designated as dry and wet. Because the temperatures of the wet cell increased rapidly from 20 to 50°C after 5.7 years of landfilling, the time t_2 corresponds to 5 years after time t_1 . Gas wellhead temperatures, shown in Fig. 4, indicate that elevated temperatures escalate from 65°C (149°F) to 90°C (194°F) in April and December of 2006, respectively. Thus, the intermediate temperature T_i remains constant from 2001 to April 2006 (approximately 4.5 years) and the time t_4 to reach T_p is approximately 6 months (October 2006). After December 2006, the temperatures follow the measured temperatures in Fig. 5. Because data reflecting long-term temperatures on landfill liners during an elevated temperature scenario are not available, the idealized temperature is assumed to remain at peak temperature T_p for 5 years (end of present data in Fig. 5). After time t_5 , the temperature decreases linearly and reaches the initial temperature T_o at time t_6 and remained constant thereafter.

Prediction of Geomembrane Service Life

The service life of HDPE geomembranes is normally evaluated using a three-stage degradation model, i.e., Stages A–C. The boundaries between Stages A–C are not, in practice, so distinct and the end of Stages B and C may vary depending on the parameters being considered, e.g., tensile break strength, tensile break strain, and stress crack resistance. Because stress cracking is the mode of final failure, the authors consider this to be the most appropriate determinant of end of life when the data are available.

Table 2. Summary of Liner Temperature Histories Examined

Case	t_1 (years)	t_2 (years)	t_3 (years)	t_4 (years)	t_5 (years)	t_6 (years)	T_o (°C)	T_i (°C)	T_p (°C)
1	5	10	—	—	20	35	20	35	—
2	5	10	—	—	20	35	20	45	—
3	5	10	14.5	15	20	35	20	35	60
4	5	10	14.5	15	20	35	20	45	60
5	5	10	14.5	15	20	35	20	45	70
6	5	10	14.5	15	20	35	20	45	80

The equations used in predicting the duration of each stage of geomembrane service life considering the idealized liner temperature history are presented herein. A detailed description of these equations is beyond the scope of this paper and can be found in Rowe and Islam (2009). The depletion of antioxidants (Stage A) is evaluated using the following equation (Hsuan and Koerner 1998):

$$\text{OIT}_t = \text{OIT}_o e^{-st} \quad (2)$$

where OIT_t = OIT remaining at any time t (min); OIT_o = initial OIT (min); s = antioxidant depletion rate (month^{-1}); and t = time (month). The antioxidant depletion rate at a temperature of interest is evaluated using the Arrhenius equation (Hsuan and Koerner 1998):

$$s = A \exp\left(\frac{-E_a}{RT}\right) \quad (3)$$

where E_a = activation energy (J/mol); R = universal gas constant (8.314 J/mol·K); T = absolute temperature (K); and A = a constant called the collision factor. Eq. (3) can be used directly to predict the antioxidant depletion rate at a constant temperature.

To accurately establish Stage B for a given geomembrane and exposure condition, it is necessary to first deplete the antioxidants and determine the initiation of a change in the physical properties of the geomembrane. The Arrhenius parameters for geomembranes during Stage B are not available because laboratory experiments have not been published at more than one elevated temperature (85°C). As a result, the duration of Stage B was calculated using laboratory data at 85°C and an activation energy of 75 kJ/mol, as reported by Viebke et al. (1994) for air-water exposed polyethylene pipe, together with the following equations:

$$\frac{s_{85}}{s_T} = \exp\left[\frac{-E_a}{R} \left(\frac{1}{T_{85}} - \frac{1}{T}\right)\right] \quad (4)$$

$$\xi = \frac{s_{85}}{s_T} \times \xi_{85} \quad (5)$$

where T = temperature of interest (K); $T_{85} = 85^\circ\text{C} = 358\text{ K}$; s_T and s_{85} = reaction rates of Stage B at temperatures T and T_{85} ,

respectively; ξ = Stage B time (years) at temperature T ; and ξ_{85} = Stage B (years) at 85°C. Eqs. (4) and (5) are applicable for predicting Stage B at a constant temperature.

The calculation procedure for the prediction of Stage C time is the same as that of the Stage B time described previously. Because Stage C Arrhenius parameters are not yet available, the duration of Stage C was calculated using laboratory data at 85°C and an activation energy of 80 kJ/mol as used by Viebke et al. (1994) for air-water exposed polyethylene pipe, together with Eq. (4):

$$\lambda = \frac{s_{85}}{s_T} \times \lambda_{85} \quad (6)$$

Because antioxidant depletion times were not calculated for the geomembrane installed at the case history facility, consideration will be given to three different 1.5 mm (60 mil) thick geomembranes (Table 3) for which data are available with respect to Stages A–C of the service life. The Arrhenius equations cited in Table 3 are used to make predictions of Stage A. Geomembrane GM1a, GM1b, and GM2 were manufactured by GSE Lining Technology, Houston, and geomembrane GM3a GM3b were manufactured by Solmax International, Québec, Canada.

For Aging Method A the geomembrane was immersed in simulated MSW leachate (no applied stress). This is the most common aging test reported in the literature (Hsuan and Koerner 1998; Sangam and Rowe 2002; Gulec et al. 2004; Rowe 2005; Rowe et al. 2008, 2009) but is likely to be overly conservative because it implies the geomembrane is exposed to leachate on both sides. If the geomembrane is located away from holes in a composite landfill liner, the top may be exposed to leachate but the bottom is usually in contact with a LHCSL and not leachate (Rowe 2005). Aging Method B (Rowe and Rimal 2008a) simulated a composite liner with the top face of the geomembrane exposed to leachate and the bottom face exposed to a hydrated GCL. In this method, there was no applied stress. Aging Method C (Rowe et al. 2010) is the most realistic and involves a full simulated composite liner [from bottom up: a sand foundation layer, geosynthetic clay liner (GCL), geomembrane, geotextile protection layer, and gravel drainage layer with circulating simulated MSW leachate] subject to a 250 kPa stress applied to the gravel leachate collection layer. Table 4 summarizes the time to complete Stage A for eight idealized cases.

In cases where the geomembrane was aged by immersion in leachate (GM1a, GM2, and GM3a), the time to antioxidant depletion is relatively small (12–20 years depending on the case). The higher end of the range (20 years, Case 1) corresponds to an idealized dry cell, i.e., no leachate recirculation, and 14 years (Case 2) for a wet cell (leachate recirculation). The lower end of

Table 3. Initial Properties and Aging Conditions of 1.5 mm Thick Geomembranes

GMB type	Aging condition	Leachate type	Std-OIT (min)		Ea (kJ/mol)
			[ASTM D3895]	Arrhenius equation	
GM1a	A	X	135	$\ln(s) = 19.85 - \frac{7084}{T}$	58.9
GM1b	B	X	135	$\ln(s) = 20.06 - \frac{7540}{T}$	62.7
GM2	A	Y	174	$\ln(s) = 20.32 - \frac{7315}{T}$	60.8
GM3a	A	Y	135	$\ln(s) = 20.37 - \frac{7304}{T}$	60.7
GM3b	C	Y	135	$\ln(s) = 20.63 - \frac{7703}{T}$	64

Notes: X = synthetic leachate consisting of inorganic nutrients, volatile fatty acids, surfactant, trace metals, and reducing agent; Y = synthetic leachate consisting of surfactant, trace metals, and reducing agent.

Table 4. Time to Complete Stage A

Case	Antioxidant depletion (years)				
	GM1a	GM1b	GM2	GM3a	GM3b
1	15	90	20	19	87
2	12	28	14	13	26
3	15	19	16	16	19
4	12	18	14	13	17
5	12	17	14	13	16
6	12	15	14	13	16

the range is 12–14 years (Cases 5 and 6) for peak temperatures ranging from 70 to 80°C. Comparing GM1a, GM2, and GM3a, initial OIT and the synthetic leachate do not significantly affect the time to deplete antioxidants for the idealized time-temperature history. As illustrated by Cases 3 and 4, the effect of intermediate temperature T_i was shown not to be a critical variable for this case study because the time-temperature history and peak temperatures controlled antioxidant depletion. For the geomembranes aged in simulated composite liner systems, e.g., GM3b, Stage A varied from 16 to 87 years for the six idealized cases.

The predictions based on leachate immersions are conservative in cases where the geomembrane is intact and leachate is only in contact with the upper portion of the geomembrane. In June 2006, the south slope near the juncture of Cells 5A and 6A failed due to elevated gas pressures, leachate outbreaks, and thermally degraded MSW. In March 2011, while the facility was excavating waste and installing a toe drain, an irregular fold, approximately 1.5 m to 1.8 m in length, of geomembrane was discovered near the junction of Cells 5A and 6A. Additional excavation showed that the irregular fold was a series of smaller folds and a tear of approximately 5 cm wide in the geomembrane. The tear resulted in leachate coming in contact with both sides of the geomembrane (simulating an immersion test), so the antioxidant depletion time is expected to be less than predicted from simulated landfill liner experiments (GM3b and GM1b). Because Stage A for geomembranes located at the facility is quite short, there is a need to examine the other stages of the service life to assess whether the geomembrane service life is adequate.

The estimated times to complete Stages B and C and evaluate the integrity of the geomembrane are summarized in Tables 5 and 6 for GM3a and GM3b. For Cases 1 and 2, the geomembrane service life is likely adequate because Stage A was completed after temperatures returned to the original ground temperature. For Cases 3 and 4, by the end of Stage A there was only a very limited

Table 5. Estimated Time to Complete Stage B

Geomembrane type	Time to complete Stage B (years)					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
GM3a	110	19	4	5	3	2
GM3b	140	120	5	4	2	1

Table 6. Estimated Time to Complete Stage C

Geomembrane type	Time to complete Stage C (years)					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
GM3a	690	690	450	390	6	3
GM3b	690	690	620	560	49	3

Table 7. Summary of Geomembrane Service Life

Geomembrane type	Time to complete Stage C (years)					
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
GM3a	690	690	450	390	6	3
GM3b	690	690	620	560	49	3

time remaining at the peak temperature (e.g., 1 year for Case 3 and GM3b); thus the predicted time in Stage C is long. Cases 5 and 6 illustrate that peak temperatures of 70 and 80°C, respectively, cause substantially shorter geomembrane service life, and the integrity of the geomembrane may be compromised. The service life of HDPE geomembranes (Table 7) is calculated by adding the durations of Stages A–C presented in Tables 4–6. The service life varied from 20 to 960 years. For situations like Case 6, the service life of the geomembrane could well be reached within the contaminating life-span. The substantial difference in predicted times is significant and highlights the need to consider the possible effects of elevated temperatures and landfill time-temperature history when designing landfills.

The predictions of Stages B and C are based on available data for stress crack resistance (GM3a). Although there were no data for GM3b in a simulated liner, available data from immersion of GM3a in leachate were used for predicting Stage B times for GM3b. Stage C has not been completed at any elevated temperature. The reported values are based on the time in Stage C at 85°C in the laboratory immersion experiments, together with the $E_a = 80$ kJ/mol used by Viebke et al. (1994) for air-water exposed polyethylene pipe. As a result, the data used to predict Stages B and C are presented in Tables 5 and 6 only to illustrate the impact of elevated temperatures on geomembrane service life. For example, the geomembrane service life of GM3b for Case 6 is approximately 20 years for the geomembrane aged with leachate present on only one side. However, the slope failure in 2006 caused the liner to tear and allowed leachate to contact both sides of the geomembrane and hence the service life could be shorter than 20 years. Given the sustained elevated temperatures and exposure conditions, the following paragraphs investigate possible indicators of the integrity of the composite liner system.

Integrity of Geomembrane Liner

Waste containment system performance data, e.g., groundwater monitoring wells, are used to assess the integrity of the composite liner system. Because the composite liner system for the case history is located below the groundwater surface, one possible indication of the loss of integrity of the composite liner system is reflected in the increased leachate volume (groundwater inflow due to an inward gradient) pumped from Cells 1 to 6. From 1999 until 2005, most of the leachate generated (103 million L) was recirculated so the volume of leachate transported off-site during this period was minimal. In 2004, the transported leachate volume was 12 million L (3.1 million gal) and continued to increase in subsequent years with 109 million L (29 million gal) in 2006 and 127 million L (33.6 million gal) in 2008. The amount of leachate generated by the effects of the reaction and subsequent combustion significantly exceeds the total amount of leachate recirculated, which may be evidence that the composite liner system is compromised. However, other potential sources of the excess leachate are (1) water generated by the heating or combustion of organic wastes (i.e., initial waste moisture content); (2) possible groundwater

inflow due to an inward gradient through the slope movement damaged liner system; and (3) rainfall infiltration.

Thermal dehydration of the MSW drives moisture from the waste, and the resulting liquid is removed via the leachate collection system or gas extraction system. The initial moisture content of the MSW was estimated to be approximately 20% because of the leachate recirculation prior to the reaction. Cells 1–6 contain an estimated 10.9 million m³ (14.3 million yd³) of airspace. Assuming both complete thermal dehydration of MSW and that half of the moisture is removed by the gas extraction system, a total increase in leachate of 605.7 million L (160 million gal) may be generated from the waste. The leachate volume was estimated using a reaction area of approximately 16 ha (approximately 45% airspace) multiplying it by 20% and a MSW unit weight of 12 kN/m³. From 2006 to 2011, approximately 654.2 million L (approximately 172.8 million gal) of leachate was transported off-site.

The sidewall liner on the south side of the landfill in the vicinity of Cell 6 was damaged due to gas pressures, leachate chemical composition, and the 2006 slope failure. Because the liner system was compromised, groundwater from the confining mine spoil and underlying shale and siltstone bedrock could have migrated into the waste mass and contributed to the excessive leachate volume because the liner system is below the zone of saturation in the mine spoil. Based on the earlier discussion, a sustained temperature of 80°C for 4 years (and even less at higher temperature) may have been sufficient to cause failure of the geomembrane. Thus, some of the excess leachate could be the result of water ingress through the liner system if the geomembrane failed.

Infiltration of precipitation is not thought to have contributed significantly to the increased leachate volume because a significant portion of the 35.7 ha (Cells 1–6 in Fig. 3) was covered with a 2.0 mm (80 mil) thick HDPE geomembrane to control odors after 2006. However, prior to placement of this cover geomembrane, surface water ponding occurred within a large bowl-shaped area at the top of the landfill created by rapid settlement of the underlying waste, which may have contributed some moisture to the leachate quantity.

The preceding discussion indicates that there is considerable uncertainty in confirming the integrity of the HDPE geomembrane. As a result, the next section provides recommendations for assessing the service life of HDPE geomembranes in the presence of elevated temperatures

Evaluation of HDPE Geomembrane Service Life

The presence of elevated temperatures at or near a liner system in the case history described earlier, as well as others, raises the question of how the service life of a liner system and, in particular, a geomembrane should be assessed. This question is usually raised after elevated temperatures have been detected and leads to many other questions, such as the criteria that should be used to assess service life, how the criteria should be investigated, and what remedial measures should be implemented for the liner system.

Examples of Possible Service Life Criteria

This issue is complicated in the United States because there is no regulation on the required service life of a HDPE geomembrane. In contrast, Ontario (Canada) Regulation 232/98 requires a service of 150 years for the primary liner system and 350 years for the secondary liner system in the double composite liner system required for a Subtitle D compliant landfill (Ontario Ministry of the Environment 1998). Based on the data presented in Table 7,

the geomembranes described previously in the elevated temperature case history would not meet Ontario Regulation 232/98 because the time-temperature history service life analysis of the 1.5 mm thick HDPE geomembrane is significantly less than 150 years. Because Subtitle D in the United States does not specify a service life as Ontario Regulation 232/98 does, some possible service life durations are listed below:

- 150 years as required by Ontario Regulation 232/98;
- Long-term performance based on monitoring criteria;
- Service life of HDPE geomembrane (Stages A–C) using time-temperature history.

Ontario Regulation 232/98 is clear about the required service life and suggests that this might be achieved for a geomembrane used in a normal MSW landfill where liner temperatures are 30–40°C (it was not written for bioreactor landfills and did not envisage codisposal with APW) provided the following requirements are met:

- The oxidation induction time of the geomembrane exceeds 100 min as determined by ASTM D3895 (ASTM 2007) or 250 min as determined by ASTM D5885 (ASTM 2006);
- The oxidation induction time of the geomembrane after oven aging at 85°C for 90 days as described in ASTM D5721 (ASTM 2008) must exceed (a) 80% of the value for the original geomembrane as determined by ASTM D3895 (ASTM 2007) or (b) 80% of the value for the original geomembrane as determined by ASTM D5885 (ASTM 2006).

Of course, a sample of the impacted geomembrane must be obtained from the facility to assess the oxidation induction time, which may be difficult because of the presence of waste and elevated temperatures.

The long-term performance of a containment barrier system, i.e., the integrity of the liner system and the components over time, can be evaluated using direct and indirect monitoring methods. The primary liner in a double-liner system is perhaps the only type of engineered barrier system in which postconstruction integrity is routinely monitored directly. Liquids collected in the leak detection layer between the primary and secondary liners provide a direct assessment of the performance of the primary liner system. For example, a double composite liner system consisting of (from top to bottom) GMB, GCL, GDC, and GMB can be an effective barrier system and provide a direct measure of the performance of the primary liner. Although leak detection layers are advantageous for monitoring large areas of barriers, based on the data, it can be difficult to distinguish the effects of LHCSL consolidation from induced flow in systems (Bonaparte et al. 2002). Indirect monitoring of engineered barrier performance by monitoring for contaminant migration downstream of a waste containment system is mandated by regulations. However, there will be a time lag between the loss of the hydraulic effectiveness of the geomembrane and contaminants being detected. The length of this time lag will depend on the site hydrogeology and the type and location of the groundwater monitoring wells being used to detect the leakage. The time lags may cause a change in the economic viability of the facility before leakage is detected, resulting in insufficient funds being available for an expensive cleanup.

Hsuan and Koerner (1995) selected the criterion for geomembrane service life as when a specific design property has been reduced by 50% of its initial value. This is referred to as the half-life of a geomembrane. Although the design property, e.g., tensile strength or strain at break, may be reduced by 50% and the geomembrane becomes brittle, the geomembrane may still function as a hydraulic barrier. Thus, this half-life concept may not be appropriate for estimating the service life of a geomembrane for containment purposes (Rowe 2012).

Using geosynthetic landfill liner simulators (GLLS), Rowe (2012) reported that when geomembranes reach the end of their service life, they experience extensive stress cracking and the number of holes goes from a few holes/ha to 30 to 100 holes/m². The geomembrane can no longer be considered functional so leakage will be controlled by the LHCSL or GCL underlying the geomembrane. It seems appropriate, then, to define the service life of HDPE geomembranes as the time from installation to onset of stress cracking, i.e., total time to complete Stages A–C, where Stage C is completed when leakage begins. Although the time to complete Stage A is well established in laboratory experiments, to accurately establish Stage B for a given geomembrane and exposure condition, it is necessary to complete Stage A (depletion of antioxidants), observe the initiation of a change in the physical properties (end of Stage B), and perform the experiment at a minimum of three temperatures (Rowe and Islam 2009). Given the quality of geomembranes, this takes a long time at all but the highest temperature examined, so limited experimental data are available to calculate Stages B and C (Rowe and Islam 2009). As geomembrane aging experiments continue to mature, it is anticipated that better estimates of Stage B and C durations will become available. In addition, not all HDPE geomembranes exhibit the same durations, e.g., antioxidant packages differ among manufacturers, so the duration of Stage A will vary. There is a large amount of uncertainty associated with evaluating the service life using Stage B through C degradation model from laboratory experiments.

The activation energies used for Stages B and C were also obtained for pipes and not geomembranes, so service life predictions may change when data become available. Because of geomembrane variations, it is recommended that service life criteria for HDPE geomembranes consider Stages A–C, where failure is defined as leakage due to stress cracking. The duration of Stage A is calculated using the time-temperature history of the site and Arrhenius parameters determined from laboratory experiments. The analyses presented in the section above titled “Elevated Temperature Case History” highlight the importance of the time-temperature history and exposure conditions in evaluating the service life of a geomembrane. For example, Cases 1 and 2 for GM3b have long Stage A completion times, and hence a service life can be expected while the geomembrane is still in Stage A. Cases 3 and 4 show that antioxidants are depleted near the end of the peak temperatures. For Cases 5 and 6, the antioxidants deplete at the beginning of the peak temperature, and so the service life of the geomembrane and remedial actions may require careful examination.

Location of Service Life Assessment

It is implicit in Ontario Regulation 232/98 (although not clearly stated) that the location where geomembrane service life should be assessed is the most critical location (i.e., that which would allow an escape of contaminant to the environment that might exceed the maximum allowable concentrations as defined in §10 of OMOE 1998). One such critical location is the sump where sustained liquid and gas pressures may be present that could facilitate advective and diffusive flow. Of course, this assumes there is no clogging of the leachate collection system that could result in sustained liquid and gas pressures accumulating at other places above the liner system besides the sump. For example, most geomembranes are placed with some wrinkles (Chappel et al. 2012; Rowe 2012). These wrinkles can result in local ponding of leachate, especially on a relatively flat landfill base, until the leachate level is high enough to flow over the wrinkle.

Another area where service life could be evaluated is landfill side slopes because the liner system, in particular the geosynthetics and the LHCSL, are subjected to tensile stress imposed by the waste, especially if it is settling due to overburden stresses, waste degradation, or waste reaction or combustion. Thus, it seems the service life would need to be met everywhere.

Possible Remedial Measures

What follows are some of the possible remedial measures that could be implemented after sustained elevated temperatures are measured on or near a liner system:

- Excavate the waste so the liner system can be repaired, as was done for a hazardous waste landfill containing industrial waste sludges and other chemical manufacturing byproducts that experienced temperatures near the liner system of approximately 800°C (Adams et al. 1997). Adams et al. (1997) describe the damage to the geosynthetic components of the liner system in the immediate vicinity of the combustion as complete disintegration, melting, or fusing of the various components together near the center of the heated area. Rippling and stretching of the materials along the perimeter of the visibly damaged area also occurred. In several areas, melted geosynthetic materials were observed in desiccation cracks in the secondary LHCSL (Adams et al. 1997).
- Install additional ground water monitoring wells down gradient of the area subjected to elevated temperature to facilitate detection of leakage. If leakage is detected, the more closely spaced monitoring wells should trigger a quicker remedial action. One of the drawbacks of this approach is that if leakage is detected, the contaminants, i.e., leachate and gas, have already entered the subsurface, which can substantially increase remediation costs.
- Stop active filling in the portion of the landfill experiencing elevated temperatures and apply a suitable low hydraulic conductivity cover to prevent infiltration.
- In addition to installing additional groundwater monitoring wells down gradient of the elevated temperature area, increase the required postclosure bonding to compensate for possibly higher remediation costs.
- The facility can perform aggressive leachate removal to minimize leachate head on the composite liner system. However, this may introduce other challenges, e.g., the case study described earlier yielded leachate quality that could not be treated locally and had to be shipped approximately 400 km for treatment at considerable cost.

Conclusions

This paper highlights some of the issues that may arise when assessing the integrity of a composite liner system in the presence of sustained elevated temperatures. Based on experiences with landfills with elevated temperatures, the following conclusions and recommendations are presented based on data and the case history presented:

1. Heat generated in landfills can be produced from a variety of sources. The reaction of metallic aluminum in APW and leachate is one such source, and data were presented to illustrate peak temperatures in an APW monofill range from 80 to 110°C. In cases such as APW, the location of the peak temperature in the landfill depends on the availability of liquid/leachate and metallic aluminum, and hence caution should be

shown when landfilling reactive wastes near the leachate collection system and composite liner system.

2. The presented case history shows temperatures at a MSW facility increased from normal operating conditions (35–45°C) to elevated temperatures (70–85°C) due to APW reactions and smoldering combustion of MSW. Thermistors installed in leachate collection pipes were used to develop a time-temperature history plot to assess the service life of the geomembrane. For GM3b, Case 1 and 2 temperatures are in the range of normal MSW landfills; the geomembrane is expected to have a service life of several centuries. When peak temperatures reach 60–80°C, the geomembrane service life can be reduced to decades for the conditions examined and thus raises concerns regarding the integrity of the geomembrane at high temperatures.
3. Although laboratory experiments evaluating the geomembrane activation energies used for Stages B and C have not been completed, the recommended criterion to estimate the service life of a geomembrane is the sum of time to complete antioxidant depletion (Stage A), Stage B, and time to stress cracking of HDPE geomembrane (Stage C). Using Arrhenius parameters for geomembranes determined via laboratory experiments and a time-temperature history plot, Stage A duration can be evaluated from Eqs. (2) and (3). An approximation of Stages B and C can be computed using Eqs. (4)–(6).
4. Assuming proper construction and operations, the service life of a geomembrane liner used in a Subtitle D landfill will depend on the temperature and time-temperature history, the chemical composition of the leachate, and the geomembrane properties. With respect to a wide range of HDPE geomembranes, the resin and antioxidant package used may have a significant impact on the geomembrane's long-term performance in landfill applications. Therefore, the selection of an appropriate geomembrane is critical to the system's long-term performance. The standard specification (GRI-GM13 1997) represents a basic starting point. While the minimum requirements may be sufficient for some applications, the GRI-GM13 specification may not be adequate for other applications such as elevated temperatures. Prior to geomembrane installation in landfills, laboratory experiments simulating higher temperatures and exposure conditions by the manufacturer or the designer are recommended to ensure adequate performance of the antioxidant package and resin to elevated temperatures.
5. Assessing the integrity of a composite liner and geomembrane is difficult and dependent on site geology and location of ground monitoring wells. For the design of new landfill cells, the barrier system should reflect the type of waste, e.g., MSW, APW, incinerator ash, and mode of operation (dry cell, leachate recirculation, bioreactor). Installing a leak detection layer below the primary liner and thermistors to monitor the temperature provides direct monitoring of the liner performance. In addition, various strategies can be adopted to control the liner temperature (Hoor and Rowe 2012) and maintain an adequate geomembrane service life.

Acknowledgments

This material is based upon work supported by the National Science Foundation (NSF) through a Graduate Research Fellowship to Navid H. Jafari. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

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